TAMPERE UNIVERSITY OF TECHNOLOGY

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LIFE CYCLE ASSESSMENT OF POWER CAPACITORS

Master's Thesis

Examiner: Professor Seppo Valkealahti
Examiner and the topic were approved in the Faculty of Computing and Electrical Engineering Council meeting on October 9th 2013

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master's Degree Programme in Electrical Power Engineering
ALAVIITALA, TIINA : Life Cycle Assessment of Power Capacitors
Master of Science Thesis, 56 pages
October 2013
Major: Electrical Power Engineering
Examiner: Professor Seppo Valkealahti
Keywords: life cycle assessment, power capacitor

During the recent years, the debate concerning climate change and other environmental threats has been in focus often. This discussion has also created pressure to business, individuals, public administrators and policymakers to integrate environmental considerations into the future decisions. Life cycle assessment is one potential tool developed to help with these decisions.

In power capacitors, polypropene or other polymer materials have been applied as a dielectric medium for several years. The recent developments in nanotechnology suggest that polymer nanocomposites could possess better qualities compared with traditional polymers not only in breakdown voltage but also in the mechanical properties such as tensile strength and Young's modulus.

In this thesis, the environmental impacts of a traditional capacitor bank and a novel polymer nanocomposite capacitor bank were assessed with the help of life cycle assessment. Process-based life cycle assessment was used to model the environmental impacts of both the traditional capacitor bank and the novel polymer nanocomposite bank. It was assumed that when a nanocomposite film is used instead of traditional polypropene film in a capacitor unit, the number of capacitor units needed would decrease by 20%. The sensitivity and the error of the assessment were studied with the help of sensitivity analysis and Monte Carlo simulation.

On average, the nanocomposite capacitor bank presented 15% smaller impacts than the traditional capacitor bank. This was also observed in the Monte Carlo simulation results. Few impact categories stood out: climate change, metal depletion and natural land transformation. The LCA results indicate clearly that especially for tin an alternative material in electronics should be searched.

It was shown in this thesis that even though nanotecnology could decrease the environmental impacts, it will not solve completely the major issues pointed out in this thesis work.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Sähkötekniikan koulutusohjelma
ALAVIITALA, TIINA: Tehokondensaattoreiden elinkaariarviointi
Diplomityö, 56 sivua
Lokakuu 2013
Pääaine: Sähköenergia
Tarkastaja: professori Seppo Valkealahti
Avainsanat: elinkaariarviointi, tehonkondensaattori

Viime aikoina ympäristöuhat kuten ilmastonmuutos, ovat olleet kiivaan keskustelun aiheina. Tämä on aiheuttanut paineita myös liiketoiminnalle, yksilöille, julkishallinnolle ja päättäjille ottaa huomioon ympäristönäkökohdat suunnittelussa ja päätöksenteossa. Päätöksenteon helpottamiseksi on kehitetty työkaluja kuten elinkaariarviointi.

Tehokondensaattoreissa on perinteisesti käytetty eristeaineena polypropeenia tai muuta polymeerimateriaalia. Uusien tutkimusten valossa on kuitenkin havaittu, että polymeerinanokomposiitit saattavat tarjota parempia ominaisuuksia perinteisiin polymeereihin verrattuna. Tällaisia ominaisuuksia ovat esimerkiksi parempi läpilyöntijännite, vetolujuus ja Youngin moduuli.

Tässä työssä tutkittiin perinteisen kondensaattoriparistoon ja uudenlaisen nanokomposiittikondensaattoriparistoon ympäristövaikutuksia elinkaariarvioinnin avulla. Molemmissa tapauksissa ympäristövaikutuksia mallinnettiin prosessi-pohjaisella elinkaariarvioinnilla. Oletuksena työssä oli, että nanokomposiitin käytöllä kondensaattoriyksiköiden lukumäärä paristossa laskee 20 %. Arvioinnin tuloksien herkkyyttä ja virhettä mallinnettiin herkkyysanalyysillä ja Monte Carlo -simulaatiolla.

Nanokomposiitin käyttö pienensi ympäristövaikutuksia, yleisesti ottaen noin 15 %. Tämä näkyy myös Monte Carlo -simulaatioiden tuloksissa. Suurimmat ympäristövaikutukset havaittiin ilmastonmuutoksen, metallien ehtymisen ja luonnon maan muutoksen kohdalla. Tulokset osoittavat, että erityisesti tinalle olisi hyödyllistä löytää ympäristöystävällisempi vaihtoehto.

Tässä diplomityössä havaittiin, että nanoteknologia ei ratkaise täysin suurimpia ongelmia, mutta sen avulla ympäristövaikutuksia voidaan mahdollisesti pienentää.

PREFACE

This thesis is not a manual or a text book on LCA. For more detailed description about the methodology, I highly recommend reading the book "The Computational Background of Life Cycle Assessment" by Reinout Heijungs and Sangwon Suh.
The work was a part of the NANOPOWER project and it was done in the Department of Electrical Engineering in Tampere University of Technology.

This project has been a bumby ride. Nothing went as it was planned but finally I managed to finish this thesis. First of all, I would like to thank Kari Kannus for the interesting, but demanding thesis topic. Unfortunately, he didn't get to see the finished thesis. I would like to thank Tuomas Mattila for all the help with this thesis, especially LCA, Monte Carlo simulation and the whole writing process. I have learned a lot. Kirsi Nousiainen helped when everything else failed. And thanks to Seppo Valkealahti (examining and commenting), this thesis is finally done. I would also like thank Alstom Grid for the data and few photos they provided for the thesis. The people in the educational services of the Faculty of Computing and Electrical Engineering helped me with the bureaucracy. Thank you for making my life so much easier. Thanks to Anne for your support. You are doing an excellent job. Special thanks go to Juha, Maija, Pasi, Saara, Cobra and Teemu. You all know what you have done. I would like thank my other friends for not abandoning me. I haven't been the nicest person during this project.

In loving memory of granny Liisa (1924 - 2013)
and
Pimu the beagle (1999 - 2013)

Tampere, 17th of October 2013

Tiina Alaviitala

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ABBREVIATIONS AND NOTATION

Abbreviations

AC	alternating current
CFC	chlorofluorocarbon
$(C_6H_6)_n$	polypropene
C_7H_8	toluene
$C_{14}H_{14}$	monobenzyltoluene
$C_{21}H_{20}$	dibenzyltoluene
CO_2	carbon dioxide
DC	direct current
1, 4-DCB	1, 4-dichlorobenzene
DEE	Department of Electrical Engineering
Eq	equivalent
HCl	Hydrochloric acid
ILCD	International Reference Life Cycle Data System
ISO	The International Organization of Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
NANOPOWER	Novel Polymer Nanocomposites for Power Capacitors
NMVOC	non-methane volatile organic compounds
ORC	Optoelectronics Research Center
PE	people equivalent
PM10	particles on the order of micrometers
ppm	parts per million
SETAC	the Society of Environmental Toxicology and Chemistry
$SiCl_4$	silicon tetrachloride
SiH_4	silane
SiO_2	silicon dioxide
SO_2	sulphur dioxide
SYKE	Finnish Environment Institute
T&D	transmission and distribution
Tekes	the Finnish Funding Agency for Technology and Innovation
U_{235}	uranium isotope
UNEP	The United Nations Environmental Program

Notation

$\mathbf{A}$	technology matrix
$\mathbf{B}$	intervention matrix
$\mathbf{C}$	characterization matrix
$\mathbf{D}$	characterization matrix
$\mathbf{f}$	final demand vector
$\mathbf{g}$	inventory vector
$\mathbf{g_{norm}}$	normalized inventory vector
Λ	intensity matrix
$\mathbf{M}$	contribution table
$\mathbf{n}$	normalization set
$\mathbf{S}$	diagonal matrix
$\mathbf{s}$	scaling vector
i	number of row in the technology matrix and the intervention matrix
j	number of column in the technology matrix and the intervention matrix
k	number of element in the inventory vector
a_{ij}	element in the row i and column j in the technology matrix
b_{ij}	element in the row i and column j in the intervention matrix
s_j	element number j in the scaling vector
g_k	element number k in the inventory vector
A	area
α	phase angle
C	capacitance
d	distance
E	electric field
E_x	energy of incineration for a substance x
e	amount of emission in kilograms
ϵ	permittivity
ϵ_0	electric constant, $8.85 \cdot 10^{-12}$ F/m
ϵ_r	relative permittivity
I	current
P	active power
Q	reactive power
Q_{comp}	reactive power produced by the capacitor
Q_{tot}	total charge
q	charge
S	real power
σ	total charge
U	voltage
V	potential difference

1. INTRODUCTION

During the recent years, the debate concerning climate change and other environmental threats has been in focus often. This discussion has also created pressure to business, individuals, public administrators and policymakers to integrate environmental considerations into the future decisions. These include considerations such as what kind of materials to use, if the production process could be more environmentally friendly or if the usage of certain materials could be decreased or a material could be replaced with another material. More knowledge is now needed about environmental aspects and hence different tools have been developed to support better decisions. [1]

Life Cycle Assessment (LCA) is one of the many environmental management tools including methods like Strategic Environmental Assessment, Environmental Impact Assessment, Environmental Risk Assessment, Cost-Benefit Analysis, Material Flow Analysis and Ecolocical Footprint. [1]

Life cycle assessment (LCA) evaluates all possible environmental impacts of a product, product system or service over the whole life cycle of a product or a product system. The life cycle of a product starts from the acquisition of raw materials from the environment and ends to the disposal of waste, via production and use. LCA consists of four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation. It is an iterative and a holistic methodology that covers only the natural environment but does not cover the economic, social or other characteristics. The results of LCA are relative values of potential impacts, not absolute values. [1, 2]

LCA is a relatively new methodology. It was developed in the 1960s to study environmental issues such as energy efficiency and pollution control. Often LCA has been utilized in comparative studies, where two or more products have been compared against each other. LCA has become a core part in environmental policy or in voluntary actions on the European Union and other countries such as the USA, Japan, Canada and Australia. Earlier, LCA studies considered only a few impact categories (for example cumulative energy use and solid waste) and the systems studied were rather simple, compared with nowadays where LCA studies are being made on topics like waste incineration, military systems or tourism with more intricate impacts such as biodiversity and noise. The scope of LCA is however growing

and impact categories that handle economical and social impacts are also considered. This is creating more sophistication to the LCA models and the methodology is growing on application, breadth and depth. [3]

During the 1990s, LCA also became part of policy documents and legislation. In the 1990s, the first scientific papers were published along with the first handbooks and guides: the International Organization of Standardization (ISO) started the work to standardize the methodology in 1994 and the LCA standards used today were published in 2006. There are two standards for the LCA methodology:

- ISO 14040: "Environmental management - Life Cycle Assessment - Principles and Framework"
- ISO 14044: "Environmental management - Life Cycle Assessment - Requirements and guidelines". [3]

However, LCA is still under development. The United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) are working on the Life Cycle Iniative while the European Commission is developing the European Platform for LCA. Furthermore, International Reference Life Cycle Data System (ILCD) has been developed to standardize the way that LCA studies are conducted and to ensure consistent quality. [1, 4]

Several LCA studies have been conducted about the production of energy, but only a modest amount of studies have been conducted considering the transmission and distribution (T&D) of electricity. There is, however a growing interest towards LCA for the components of the power grid. So far, Norwegian [5] and British [6] power transmission grids as well as overhead lines and underground cables [7, 8, 9] have been analyzed with LCA. Transformers, substation equipment [10] and the environmental burdens of different materials used in the electricity transmission have also been studied with LCA [11].

Novel Polymer Nanocomposites for Power Capacitors (NANOPOWER) project is a part of Functional Materials, a programme funded by the Finnish Funding Agency for Technology and Innovation (Tekes). It is done in collaboration with Department of Electrical Engineering (DEE), Optoelectronics Research Center (ORC) (Tampere University of Technology), VTT Technical Research Centre of Finland and Nanoscience Center (University of Jyväskylä). The main objectives of the project are to produce novel electrically insulating polymer nanocomposites and films in a pilot scale for power capacitors. One part of the NANOPOWER project was to conduct a life cycle assessment for the traditional and polymer nanocomposite capacitors. [12]

This thesis performed the LCA study for NANOPOWER project and it was conducted in collaboration with Finnish Environment Institute (SYKE). The objectives of this study were:

1. to investigate, what kind of results can be attained with LCA methodology and if they can assist in the design and the manufacturing of power capacitors
2. to perform a LCA for a capacitor bank that is manufactured and used at the moment
3. to perform a LCA for a novel capacitor bank that has polymer nanocomposite as a dielectric medium and
4. to find possible hot spots in the manufacturing process of both of these constructions.

The LCA methodology is presented in Chapter 2, where the history, advantages and limitations of the methodology will be discussed along with the theory of LCA and the computational background. Power capacitors, polymers and polymer nanocomposites are presented in Chapter 3. Chapter 4 focuses on the methods and data used in this study and Chapter 5 contains the results and discussion. The final chapter, Chapter 6, includes the conclusion.

2. LIFE CYCLE ASSESSMENT

2.1 Introduction

LCA is a methodology for evaluating possible environmental impacts over the whole life cycle of a product or a product system. The life cycle is considered to begin from the acquisition of raw materials from the environment via production and use, and to end in the disposal of waste. LCA commonly contains the life cycle from "cradle-to-grave" and recycling is also considered a part of the life cycle of a product. LCA does not give absolute results about the environmental impacts; the results are relative values of potential impacts. LCA covers not only the natural environment, but also to human health and resource depletion. [1]

LCA can be used for analyzing the origins of problems related to a particular product, comparing the improvement variants of a given product, designing new products or choosing between a number of comparable products. For example, LCA can be used to pinpoint possible environmental hot spots in a product manufacturing system, to assign a "green label" for environmentally friendly product alternatives (eco-labelling) or to design more environmentally friendly products (eco-design). [13]

2.2 Methodology

LCA consists of four phases:

1. Goal and Scope Definition
2. Life Cycle Inventory Analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation.

LCA is an iterative technique, which means that individual phases can use the results of other phases. For example, it is possible to return to the begin and adjust the goal and scope if necessary [2]. The iterative nature of LCA is shown in Figure 2.1.

The iterative approach improves the consistency and the comprehensiveness of the study and the reported results. [1, 14]

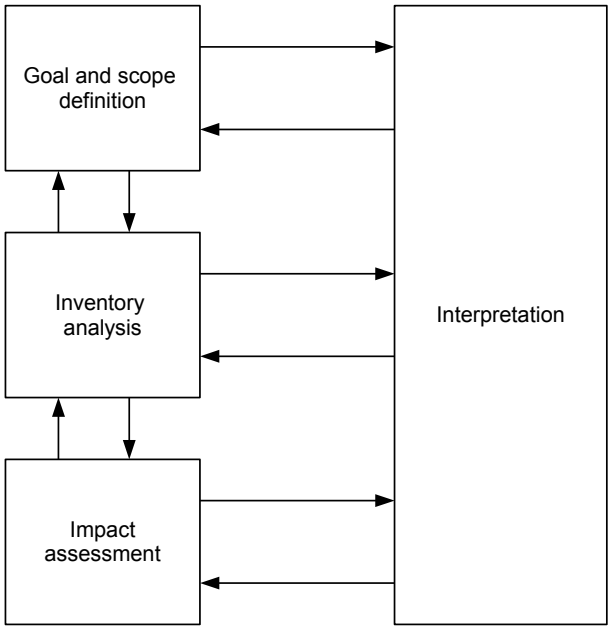

Figure 2.1: *Illustration of LCA phases. The arrows represent the iterative nature of the methodology. [2]*

Life Cycle Assessment is also a relative approach. The results are not absolute and do not predict actual impacts, only potential ones [15].

The Goal and Scope Definition is the first step of an LCA study. System boundaries, study assumptions and limitations, data requirements and if a critical review is necessary is defined during this phase. The goal of the study includes the intended application, reasons for carrying out the study, intended audience and if the results are used in comparative assertions disclosed to the public. [2]

The functional unit is one of the most important decisions in the scope definition. The functional unit is the quantified performance of a product system for use as a reference unit [2], for example, ”emissions for one ton of goods transported for a thousand kilometers”. The results of LCA are relative and LCA is structured around the functional unit. If the functional unit is not defined, it will be difficult to attribute environmental loading and consumption to the product. [15]

The inventory analysis (LCI) includes the gathering of data and certain calculation procedures. Data is usually gathered from various sources: it is considered primary, when it is acquired for example from suppliers or manufacturers and secondary, when data is acquired from literature. [15]

The data can be divided within the boundaries of the study to inputs such as

- energy inputs, raw material inputs, ancillary inputs and other physical inputs
- products, co-products and waste
- emissions to air
- discharges to water and soil
- other environmental aspects. [2]

From this data, a compilation of inputs and outputs (resources and emissions) is defined based on the goal and scope definition [1]. The data is further verified with calculation procedures such as data validation, and relating the data to unit processes and to the reference flow of the functional unit. Allocation of data is also included in the LCI phase [2]: it is used to divide the emissions of multi-functional processes to single products. For example, combined heat and power production produces electricity. The use of emissions and fuel can be allocated between these products based on energy content, exergy and technological knowledge of monetary value. The rules of allocation have to be consistent throughout the inventory collection.

The final step of LCI is the assessment of the limitations of the analysis. The data quality and sensitivity analysis is performed to the choice of methodology and to all significant inputs and outputs. The results of the LCI need to be further developed to acquire environmental impact data. [15]

Based on the LCI phase, the magnitude and the significance of the potential impacts are evaluated in the life cycle impact assessment (LCIA). This is done by three mandatory steps:

- the selection of impact categories, category indicators and characterization models
- characterization
- classification. [15, 2]

Usually, the results of LCIA are also normalized and grouped [2].

The data is divided into environmentally relevant categories in classification and these categories are reduced to single metrics for each category in characterization [15]. The characterization can be performed either by midpoint modelling or endpoint modelling. In midpoint modelling, an indicator is chosen somewhere between emission and endpoint in the environmental mechanism. This is used as a model for the impact of this indicator. For example, carbon dioxide, nitrous oxide and

fluorocarbons are converted into global warming potential and expressed as carbon dioxide equivalents [16]. An alternative method to achieve single metrics is to analyze at the endpoint impacts of emissions. In that approach, emissions are converted directly into damage to human health (life years lost), ecosystems (species lost) and resources (additional costs). In the endpoint modelling, the entire environmental mechanism is included in the characterization model and often the variables in the endpoint modelling are of direct social concern. The midpoint model is relatively robust, but the impact categories are difficult to interpret. The endpoint model has only a few, easy to understand indicators, but the uncertainty is greater. [1]

The impact category is a class that represents environmental issues of concern to which the LCI results may be assigned [2]. A category indicator is a metric that represents the environmental mechanism that the category affects the environment [15].

All the results from these three previous phases are evaluated in the Interpretation in relation to the goal and scope. In this phase, conclusions and recommendations are made based on the results of the LCIA, hotspots in the product systems are identified, and contribution analysis and sensitivity checks are performed. The interpretation may result in answers to the study questions or redefining the goal and scope and further to another iterative round in the study. [1, 14]

There are some requirements for an LCA study. First, LCA should be transparent and comprehensive. Transparency is necessary because LCA is a complex process and otherwise the results may not be interpreted correctly. In order to the study be comprehensive, LCA must consider natural environment, human health and resources. Second, the scientific approach is also important. Decisions must be made primarily based on natural sciences, but if that is not possible, decisions can be made based on for example social and economic sciences or international conventions. Otherwise, decisions can be based on value choices. [2]

LCA can be performed with software such as SimaPro (commercial) or OpenLCA (free), but the LCA model and calculations are also possible to compute manually using Matlab or spreadsheet software such as Microsoft Excel or Libre Office Calc. In LCA software, the program calculates the model and the results based on the inputs of the user. When LCA is calculated manually, the LCA model is constructed by the user [14]. The computational side is the same, no matter whether one uses software or does the assessment manually. When LCA is calculated manually, the user observes all the connections between processes and material/energy flows easily. This is not the case when LCA software is used [1]. Earlier the matrix model produced more accurate results since the matrix calculations were not employed by the software. Nowadays the software use matrix based calculations presented in the next chapter. [14]

Data about certain processes and products can be found in databases such as the Swiss ecoinvent. [1]

2.3 Computational Background

In the following chapter, the computational background of LCA is presented. Most of the notations for the matrices and the vectors come from the book "The Computational Background of Life Cycle Assessment" by Reinout Heijungs and Sangwon Suh. [14]

First, the functional unit that was defined during the goal and scope definition is formulated to a final demand vector **f**. This vector has only one non-zero value which is the same as the defined functional unit.

For the LCA calculations, the second step is to construct a system, that represents the quantified flows connected to unit processes. A technology matrix **A** has to be formulated first. **A** represents the flows within the economic system and it should be an invertible matrix. In order for **A** to be invertible, it has to be also a square matrix.

The first step in compiling **A** is to describe the processes that produce the functional unit. The processes are presented in columns. After this, the inputs and outputs (rows) for each process are described and the processes needed to produce these inputs and outputs are defined. This is then repeated, until all processes are defined and all the inputs and outputs have been defined from cradle-to-grave. The inputs to the system are negative numbers while outputs are positive. The columns can be also thought as unit process vectors which describes what resources are needed and what emissions are produced while performing that process.

The technology matrix **A** and intervention matrix **B** is formulated in the inventory phase. The data is gathered for the primary processes and connections are made for secondary processes into the **A**. Often the assessment cannot be fully calculated using primary data in which case databases such as ecoinvent [17] are needed.

After a technology matrix **A** has been formulated, the scaling vector **s** has to be calculated. It can be accomplished by calculating the inverse of **A** and multiplying it with the final demand vector **f** (2.1)

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{f}. \tag{2.1}$$

The columns of inverse **A** illustrate how many of other processes are necessary for the production of one output of the product represented by the column.

The intervention matrix **B** represents the environmental interventions of unit processes. The columns of **B** have the same processes as in **A**, but the rows represent impact categories such as agricultural land occupation, marine ecotoxicity and water

depletion. They are known as unit emissions or unit impacts.

When **B** is multiplied with **s**, the result is

$$\mathbf{g} = \mathbf{Bs}, \tag{2.2}$$

where **g** is the inventory vector. This (2.2) is the final outcome of the life cycle inventory phase of analysis.

Inserting 2.1 to 2.2, **g** can also be written

$$\mathbf{g} = \mathbf{BA}^{-1}\mathbf{f} = \mathbf{\Lambda f} \tag{2.3}$$

where Λ is the intensity matrix. The intensity matrix is calculated for the whole system. The rows of the intensity matrix describe the life cycle environmental impacts of the processes described in columns. As such, it includes the "environmental footprints" of all the products of the system. These include the product which supplies the functional unit.

Equation 2.3 is valid only when the values in **B** are already characterized. If the characterization is not done earlier, two more matrices have to be defined: **C** and **D** [14]. **C** contains the characterization factors that convert individual emissions to midpoint or endpoint impact results. **C** commonly originates from ReCiPe [16] or some other LCIA model. **D** contains the unit emissions of the analyzed processes. They can be collected from primary data or from databases. In this case, part of **A** comes also from these databases. The intervention matrix **B** is now

$$\mathbf{B} = \mathbf{CD}, \tag{2.4}$$

and the inventory vector **g** can be written as [14]

$$\mathbf{g} = \mathbf{CDA}^{-1}\mathbf{f}. \tag{2.5}$$

Equations (2.4) and (2.5) are the first stages of the impact analysis. This step is called the characterization of the LCI results.

For a contribution table **M** (2.6), a diagonal matrix **S** has to be formed. In matrix **S**, the entries in the main diagonal come from the vector **s** while the rest of the entries are zero. This matrix is then multiplied with Λ.

$$\mathbf{M} = \mathbf{\Lambda S} \tag{2.6}$$

The result is the contribution table, that shows the part of each unit process from the total impacts.

The inventory result can be normalized in the LCIA phase. The normalization

factors are found in the corresponding LCIA methodology (for example ReCiPe) [16]. Each characterization model ($\mathbf{C}$) includes its own normalization set $\mathbf{n}$. These results represent the average environmental impacts of an European person. Using these normalization factors, the values of $\mathbf{g}$ can be compared with the emissions of an average European (2.7)

$$\mathbf{g_{norm}} = \mathbf{g n^{-1}}, \tag{2.7}$$

where $\mathbf{g}_{norm}$ contains the normalized values of $\mathbf{g}$. [14, 16]

2.4 Evaluation of Results

LCA is often a comparative study, where various products, processes or other systems are being compared. This comparative nature may cause error in the results and hence, some kind of uncertainty analysis should be considered.

Possible sources of uncertainty in LCA include:

- the data that is used in the inventory analysis (elementary flows)
- the data that is used in the impact assessment (inventory flows in environmental impact scores)
- the assumptions that are made when constructing the system
- the choices that are made on central decisions (allocation key, impact assessment methodology, future developments chosen).

Usually, the uncertainty in LCA results can result from stochastic uncertainty, choice uncertainty or the lack of knowledge of the studied system. Stochastic uncertainty can be addressed either with analytical approach or with simulation. Choices are more difficult to address, since they are often discrete by nature. Lack of knowledge of the studied system is not handled by quantitative uncertainty assessment, but the error can be shown in qualified peer review.

When the uncertainty in stochastic data is addressed, distribution type, mean and variation for the process and assessment data must be known. The analytical solution may become complex even for small systems but it is often approximated with Taylor series. The Taylor series represent the error on the results as a function of the error on the process data for each process. However, simulation is preferred since the analytical approach requires qualified simplifying assumptions in order to be operational.

Since the results may contain uncertainty or bias, the over-intepretation of results must be avoided. The uncertainty assessment does not detect systematical errors or gaps in the model or data. [4]

2.4.1 Sensitivity Analysis

LCA matrices tend to be very large which leads to many different data points and hence many possible error sources. It would be laborious to study all the variables in the technology and intervention matrices and hence the potential candidates for example Monte Carlo simulation should be selected somehow. One of the methods for this is the sensitivity analysis.

Suppose, that an output variable z (2.8) depends on two input variables x and y and the output can be expressed as

$$z = f(x, y). \tag{2.8}$$

The change of z (2.9) in respect of x and y is (when the change is marginal)

$$\Delta z = \frac{\partial z}{\partial x}\Delta x + \frac{\partial z}{\partial y}\Delta y. \tag{2.9}$$

In this equation, Δz is the marginal change of z, Δx the marginal change of x and Δy the marginal change of y.

The sensitivity coefficient $\frac{\partial z}{\partial x}$ can now be calculated (2.10)

$$\frac{\partial z}{\partial x} = \frac{\partial f(x, y)}{\partial x}, \tag{2.10}$$

which calculates the sensitivity coefficient of a function f with respect to the input parameter x.

For the technology matrix (2.11) it is known that

$$\mathbf{As} = \mathbf{f} \tag{2.11}$$

.

In sensitivity analysis, final demand vector $\mathbf{f}$ is assumed unchanged and the change of $\mathbf{f}$ infinitesimally small.

If the change of $\mathbf{A}$ is $\Delta\mathbf{A}$ and the change of $\mathbf{s}$ is $\Delta\mathbf{s}$ the new form of equation (2.11) is now

$$(\mathbf{A} + \Delta\mathbf{A})(\mathbf{s} + \Delta\mathbf{s}) = \mathbf{f}. \tag{2.12}$$

After expanding the parentheses, the result is

$$\mathbf{As} + \mathbf{A}\Delta\mathbf{s} + \Delta\mathbf{As} + \Delta\mathbf{A}\Delta\mathbf{s} = \mathbf{f}. \tag{2.13}$$

It should be noted, that $\mathbf{As}$=$\mathbf{f}$ which reduces (2.13) to

$$\mathbf{A}\Delta\mathbf{s} + \Delta\mathbf{A}\mathbf{s} + \Delta\mathbf{A}\Delta\mathbf{s} = 0. \tag{2.14}$$

When (2.14) is further calculated, $\mathbf{s} = \mathbf{A}^{-1}\mathbf{f}$ and it is assumed that $(\mathbf{A} + \Delta\mathbf{A})$ is reversible, the result is

$$\Delta\mathbf{s} = -(\mathbf{A} + \Delta\mathbf{A})^{-1}\Delta\mathbf{A}\mathbf{A}^{-1}\mathbf{f}. \tag{2.15}$$

If $\Delta\mathbf{A}$ is assumed infinitesimally small, (2.15) it can be written as (2.16)

$$\frac{\partial\mathbf{s}}{\partial a_{ij}} = -\mathbf{A}^{-1}\frac{\partial\mathbf{A}}{\partial a_{ij}}\mathbf{A}^{-1}\mathbf{f}, \tag{2.16}$$

where a_{ij} is the element a of the matrix $\mathbf{A}$ in the i row and the j column.

From (2.1), (2.4) and (2.3) it results

$$\mathbf{g} = \mathbf{B}\mathbf{s}. \tag{2.17}$$

Derivatives of (2.17) are

$$\frac{\partial\mathbf{g}}{\partial a_{ij}} = \frac{\partial\mathbf{B}}{\partial a_{ij}}\mathbf{s} + \mathbf{B}\frac{\partial\mathbf{s}}{\partial a_{ij}} = \mathbf{B}\frac{\partial\mathbf{s}}{\partial a_{ij}} \tag{2.18}$$

and when (2.16) is applied to (2.18) this results in

$$\frac{\partial g_k}{\partial a_{ij}} = -(\mathbf{B}\mathbf{A}^{-1})_{ki}s_j \tag{2.19}$$

where g_k is the k element of the vector $\mathbf{g}$.

This can be also written as (2.20)

$$\frac{\partial\mathbf{g}}{\partial\mathbf{A}} = -(\mathbf{B}\mathbf{A}^{-1})_{ki}diag(\mathbf{s}) \tag{2.20}$$

For the inventory matrix, the derivatives (2.21 are

$$\frac{\partial\mathbf{g}}{\partial b_{ij}} = \frac{\partial\mathbf{B}}{\partial b_{ij}}\mathbf{s} + \mathbf{B}\frac{\partial\mathbf{s}}{\partial b_{ij}} = \frac{\partial\mathbf{B}}{\partial b_{ij}}\mathbf{s} \tag{2.21}$$

where

$$\frac{\partial\mathbf{g}}{\partial\mathbf{B}} = \begin{cases} 1 & \text{if } i = k \\ 0 & \text{otherwise} \end{cases}$$

.

The sensitivity coefficients of $\mathbf{B}$ compared to $\mathbf{g}$ can be calculated now with (2.22)

$$\frac{\partial \mathbf{g}}{\partial \mathbf{B}} = \mathbf{B} diag(\mathbf{s}) \mathbf{g}^{-1} \tag{2.22}$$

The sensitivity coefficient represents the proportion of the whole environmental impact that flows through on particular process-input/output knot. In other words, if the value of specific element in the matrix changes, what kind of effect it will have on the whole environmental impact. If the value of the sensitivity coefficient is < -1 or > 1, the element in the matrix is significant and should be always chosen for further examination. If the value is more than 0.1 more examination should also be considered, but if the value is less than 0.01 it is considered insignificant. [14, 18]

Possible candidates for further studies such as simulation are chosen based on sensitivity coefficients and uncertainty factors. The uncertainty factors can be defined based on literature or by using the pedigree matrix. The pedigree matrix is a tool for quantifying uncertainty. With the help of the pedigree matrix, the uncertainty factors can be calculated from a known mean value. [19]

2.4.2 Monte Carlo Method

Sensitivity analysis is often useful when there is only one variable studied. However, in LCA there are often several variables which combined effect has to be estimated. Due to this, Monte Carlo simulations are applied for the propagation of uncertainty. This method can be used for analysing various research fields such as mathematics, science, industry, commerce and entertainment.

In the Monte Carlo method, random numbers are generated and then employed by computer algorithms [20]. For Monte Carlo simulation of LCA, it is assumed that all processes and elementary flows are independent and their variation is independent of other values. Based on the sensitivity analysis, each piece of inventory data is varied independently. The variation occurs around the median of the value following the distribution which is specified for it. The inventory result is calculated and stored and this is repeated with another variation of the inventory data. A distribution is calculated from the calculated inventory and this will approach the true distribution of the results. This will require several repeated calculations, often above 1000 iterations. As a result, an estimate for the variation around the median is found for the final results. [4]

Two random sampling procedures are possible for Monte Carlo simulation in LCA: Simple Random Sampling and Latin Hypercube Sampling. In the first one, a random number is sampled from each distribution specified for every uncertain model parameter. This results in a single estimate for the desired endpoint. This calculation is repeated several times (around 1000) and the result is a probability

distribution of the model endpoint. Latin Hypercube Sampling is more effective when sample size is larger than 1000. In this method distribution for each parameter is divided into sections of equal probability. [21]

Often the variables studied in the Monte Carlo method are found using sensitivity analysis (described in subchapter 2.4.1.) [4]. The results are presented either with using probability distribution function or with cumulative distribution function [22].

The uncertainty simulation of LCA results is often performed with the Monte Carlo method, but there are also other options, such as

- the differential uncertainty analysis
- the Monte Carlo analysis of statistical simplifications of complex models
- non-probabilistic methods
- first-order analysis employing Taylor expansions. [21]

2.5 Advantages and Limitations

There are three major advantages of LCA. First, it provides a holistic view of the interaction between a product system and the environment. Second, it advances the understanding and the general awareness of the correlation of environmental consequences. Last, LCA presents relevant information about potential environmental activities such as environmental hot spots in the manufacturing process of a product for the decision makers. This may help to identify possible environmental improvement opportunities. [15]

Due to the fact, that LCA is a relative approach, it only provides results for potential impacts but not the absolute ones. LCA can assist in the decision making process, but it cannot substitute for example Environmental Risk Assessment [1]. LCA is not an accurate prediction about absolute impacts since the potential impacts are presented in relation to a reference unit. Also, the environmental data is a combination of data from various places and times, the modelling of environmental impacts is uncertain to a point and some of the impacts are clearly future impacts. [2]

LCA has a holistic nature, which is both a strength and a weakness. LCA cannot address localized impacts and it is usually a steady-state approach. All processes are considered linear in LCA, which is not the case in actual processes and product systems.

Since LCA is an environmental assessment method, it does not take a stand on economic, social or other characteristics. Further on, LCA only considers the physical characteristics of the industrial activities. LCA should be based on natural

sciences, but often numerous technical assumptions and value choices must be made in order to conduct the assessment. For example, how to allocate the burdens of combined heat and power to the produced electricity and heat. Availability of data can also pose some problems in LCA. [13]

3. POWER CAPACITORS

A power capacitor is a device used for compensating reactive power in the electric grids. The construction is usually a capacitor bank, where several capacitor units are connected in parallel and/or in series depending on the reactive power needed.

Power capacitor banks are used for power factor correction and series compensation. Generally, power is compensated at the use site, instead of producing reactive power in a power plant and transferring it to the site. Power factor correction is important in the grids, because connected equipment such as transformers and air-conditioning cause the phase angle between the current and the voltage. [23]

The connection between the apparent power S and the current I (3.1) is

$$\underline{S} = \underline{U}\underline{I}^* \tag{3.1}$$

where $\underline{S}$ is the apparent power, $\underline{U}$ is the voltage and $\underline{I}^*$ is the complex conjugate of current in the system. The apparent power is a complex quantity (3.2), which can be defined with the real power (P) and the reactive power (Q) or the phase angle (α)

$$\underline{S} = P + jQ = S\angle\alpha. \tag{3.2}$$

This relation is illustrated in Figure 3.1.

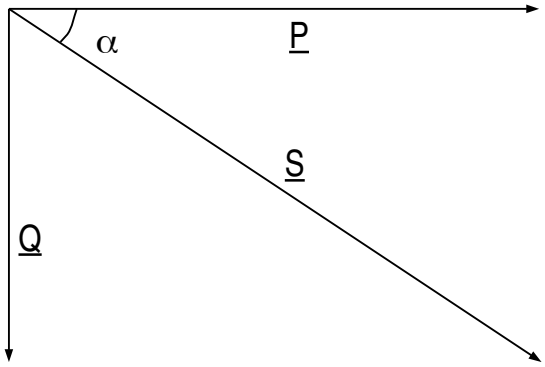

Figure 3.1: *The relation between apparent power, active power, reactive power and phase angle. The active power is real and reactive power is complex. The length of $\underline{S}$ is the absolute value of apparent power. [24]*

The active power is the only form of power that is converted into useful mechanical energy. The reactive power is the power that is stored to the electric field and is the power that is used for power compensation.

The maximum active power is transferred when the phase angle between the current and the voltage is zero. When the phase angle increases or decreases, the transferred active power also decreases. After the phase angle changes, more current is needed to transfer the same amount of active power. In the electric grid, most of the components are inductive (components that use reactive power) which causes the current to fall behind the voltage. In this case, the phase angle is positive since the apparent power is defined using the complex conjugate of the current. [24, 25]

The effect of power compensation is illustrated in Figure 3.2, where Q_{comp} is the reactive power produced by the capacitor.

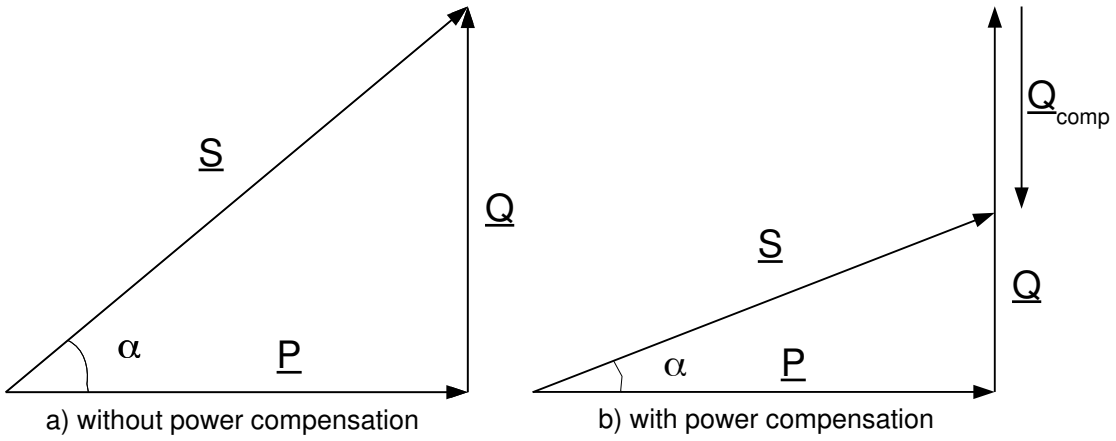

Figure 3.2: *The effect of power compensation. The apparent power transferred is smaller when capacitors are used for power compensation. This will also decrease the phase angle α. $\underline{Q}_{comp}$ is the reactive power produced by the capacitor. [24, 25]*

Series compensation is used to reduce the voltage drop in the line, prevent voltage collapse, increase steady-state power transfer and increase the transient stability limit. During a voltage drop, the amount of useful power decreases and the transmission capacity of the line reduces. A capacitor bank decreases the impedance of the transfer line and thus increases the voltage of the line. Series compensation using capacitors is cost-effective and almost maintenance free.

The benefits of power compensation are economical and environmental. Power compensation saves the cost of reactive power, reduces the cost of investment and saves money by reducing active power losses. [23]

3.1 Capacitor Basics

A capacitor is a passive component that can store energy in to the electric field and release energy quickly. It consists of two conductive electrodes and an insulating medium in between. One of the electrodes is charged positively, the other negatively. Electric charge and potential energy is stored into the electric field in the insulating medium, also known as a dielectric.

A typical construction for a capacitor is two conducting plates made for example metals insulated from each other by the dielectric (see Figure 3.3). The dielectric in between is a material, that can become polarized and has no free electrons.

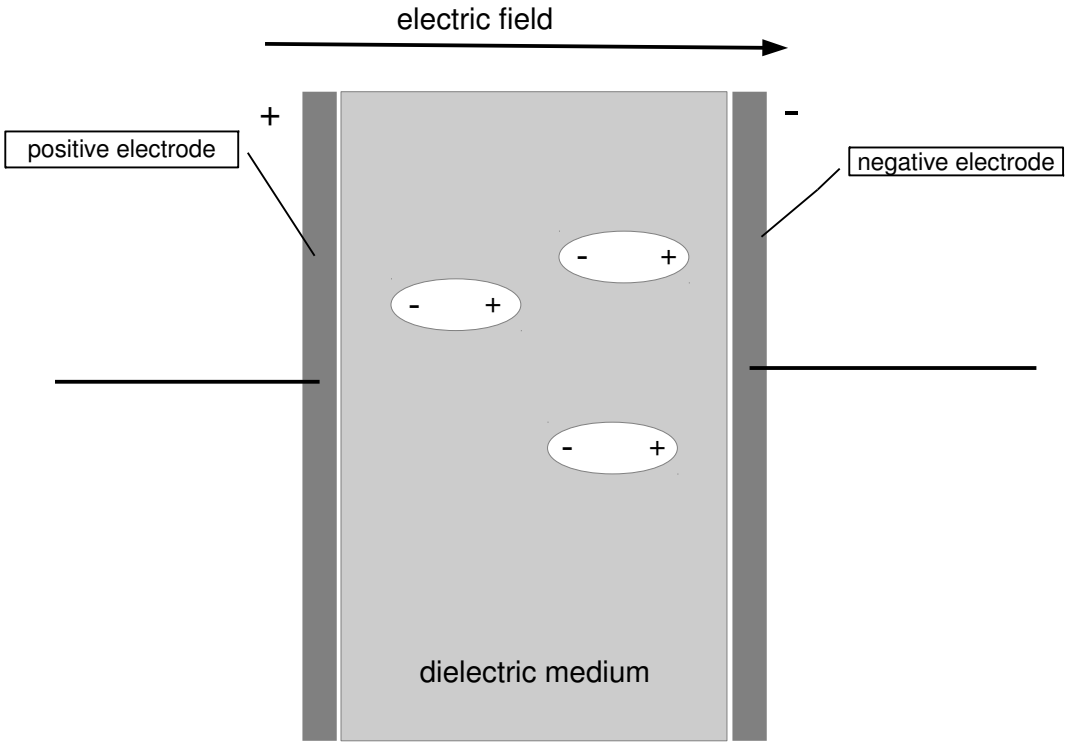

Figure 3.3: *The basic structure of capacitor and the effect of the electric field. The molecules of the dielectric medium become polarized when an electric field is induced between electrodes. One of the electrodes becomes positively charged and the other negatively. The molecules in the dielectric medium become polarized. The dipoles turn oppositely to the electric field. [26]*

In a insulating material, the outer electronic shell of the atom is full and the energy necessary to remove an electron is large. Due to this, there are no free electrons to act as charge carriers. In conductors, the outer shell is not full and the electrons can move freely between atoms. Hence there are free electrons to act as charge carriers.

Polarization is the redistribution of positive and negative charges in a dielectric

material. In polarization, the dielectric material is subjected to an electric field and the dielectric material remains electrically neutral on the outside. Polarization causes a decrease in the electric field after the electric field has moved the negative and positive charges towards opposite charged electrodes. Polarization also increases the ability to store charge in the insulating material. [26, 27]

Polarization can occur in various mechanisms. These include:

- electron polarization
- atom polarization
- dipole polarization
- space charge polarization.

In electron polarization, the electron cloud around the nucleus moves in the electric field in relation to the nucleus. In atom polarization, the negatively and positively charged atoms move according to the electric field. Dipole polarization occurs in organic molecules, where the molecule dipoles turn so that the dipole moment of the molecule is parallel to the electric field. Usually, the dipole polarization is not complete due to molecule friction and the moment of inertia of the molecules.

Space charge polarization is the slowest form of polarization. It occurs in the interfaces of heterogenic insulating materials, such as oil-impregnated paper. The electric field causes the positive and negative charge carriers to accrue to the interfaces. [27]

The type of the insulating material depends on the type and the use of the capacitor in question. Possible insulating materials include gas, air and organic or inorganic films.

The ability of capacitor to store energy is called capacitance (C) (3.3), which unit is farad (F). One farad is considered a large value for capacitance and hence generally the magnitude of the capacitance is either microfarad (10^{-6}), nanofarad (10^{-9}) or picofarad (10^{-12}). The capacitance can be compared to the work needed to charge the capacitor and it is defined as the ratio of charge (q) to the potential difference (V)

$$C = \frac{q}{V}, \tag{3.3}$$

Usually, the capacitor consists of two metal films or plates, with area of A. The metal films are separated from each other with a distance d which is usually very small compared with the other dimensions. On this account, the magnitude of the electric field E in vacuum (3.4) is defined as

$$E = \frac{\sigma}{\epsilon_0} = \frac{q}{\epsilon_0 A}, \tag{3.4}$$

where σ is the total charge Q_{tot} divided by the area A and ϵ_0 is the electric constant, $8.85 \cdot 10^{-12}$ F/m. The field is considered uniform and thus resulting (3.5)

$$V = Ed = \frac{1}{\epsilon_0}\frac{qd}{A}. \tag{3.5}$$

In this case, capacitance (3.6) is

$$C = \frac{q}{V} = \frac{q}{\frac{1}{\epsilon_0}\frac{qd}{A}} = \epsilon_0\frac{A}{d}. \tag{3.6}$$

The capacitance depends on the shape and size of the conductors and the insulating materials characteristics. When the capacitance increases, the charge increases for a given potential difference which eventually increases the amount of stored energy. One typical construction of a capacitor is presented in Figure 3.4. This construction provides capacitance of several microfarads in a compact package. [26]

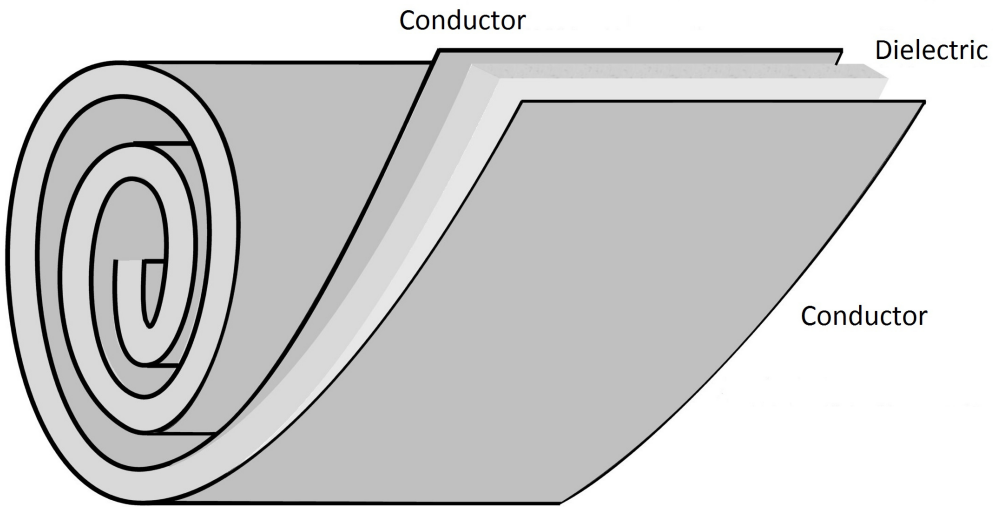

Figure 3.4: *A common type of capacitor construction. Dielectric film layers separate thin conducting films from each other and these are then rolled. Often dielectric films are also located on the outside of conducting films. [26]*

The insulating material between the capacitor electrodes can be gas, liquid, solid or vacuum. There are, however, some benefits in using solid insulating materials in capacitors. First, the dielectric works as a support system for the thin metal sheets with very little separation without contact. Second, the dielectric increases the maximum potential difference between the metal sheets. Last, the capacitance of a capacitor improves comparing to air when an insulating material is used.

Equation (3.6) is only valid in capacitors, where the insulating material is air. When a dielectric, like polypropylene, is used, the capacitance increases. For this

reason, the capacitance has to be defined differently (3.8), with the help of a quantity called permittivity (ϵ) [26]. For insulating materials, permittivity is often represented as relative permittivity, ϵ_r. It can be defined as (3.7)

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}. \tag{3.7}$$

Equation (3.8 describes the relation between the dielectric medium and the electric field. When a dielectric is placed in between the conducting plates, the potential difference increases that increases the electric field between the electrodes.

With a dielectric, the capacitance is defined as [26]

$$C = \epsilon \frac{A}{d}. \tag{3.8}$$

Capacitors can be divided into three groups: electrolytic, ceramic and film capacitors. Electrolytic capacitors are divided between aluminum and tantalum electrolytics; the aluminum electrolytics have been impregnated in liquid, while the tantalum electrolytics are dry. The film capacitors are divided into polymer, mica (a group of phyllosilicate minerals) or paper capacitors.

An electrolytic capacitor has a moderate energy and power density, while the losses and the dissipation power factor are high [28]. The dissipation factor illustrates the difference between the insulating material and an ideal insulating material [27]. The circuit is also polarity dependent making electrolytic capacitors useful in the direct current (DC) circuits. Usually, the capacitance of these capacitors is high (1 to 100000 microfarads) and these are used for example in filtering and rectified circuits.

Ceramic capacitors provide moderate energy density, high power density and formulation-dependent losses. The size of ceramic capacitors varies from very small to moderate (10 to 100 microfarads). Ceramic capacitors are used in low voltage DC control circuits for example low frequency filtering and buffering.

Film capacitors consist of either polymer, mica or paper insulating material and are readily scalable with high reactive power, modest energy density and quite high power density. Film capacitors are polarity independent and they have moderate to large capacitance values ($>>$ 100 microfarads). Film capacitors are used in high power electronics, for instance pulse-duty circuits, high frequency filtering and power factor correction.

Some new technologies are also being developed. These technologies include chemical double layer capacitors, which have high energy density, lower power density and modest voltage in DC circuits. These are used as energy storage for electric cars, reservoir capacitors for switched mode power systems and power multipliers

for battery powered systems. [28]

3.2 Structure and Materials of Power Capacitors

3.2.1 Basic Structure

A power capacitor unit consists of coils with aluminum foil and polypropylene film, wiring, fuses and discharge resistors that are wrapped in pressboard and paper. Wiring is pulled outside the structure and connected to lead-in wires. The structure is mounted in a steel case and a steel hood is welded on with lead-in insulators. Lead-in wires are soldered to the insulators. Three different power capacitors are shown in Figure 3.5.

Figure 3.5: *Typical power capacitor units. Photo provided by Alstom Grid, published with permission.*

The capacitor case is then dried and impregnated with impregnating oil [27].

Impregnating oil protects polypropylene from ultra violet radiation [29] and prevents the oxidation of aluminum to aluminum oxide. The reaction where aluminum transforms to aluminum oxide occurs easily, since aluminum is such a good reducing agent and it will even extract oxygen from other metal oxides. Aluminum oxide, also known as alumina is an insulating material, with permittivity around 10. [30, 31]

The openings are closed with brass screws and the capacitor is sandblasted, painted and tested. [27]

3.2.2 Capacitor Coils

Capacitor coils are made from aluminum foil and polypropylene film. The aluminum foils are usually few micrometers thick. Two identical aluminum foils are insulated from each other by several polypropylene film layers between the aluminum electrodes. Aluminum foils and polypropylene films are then rolled in to a coil and then flattened (see Figure 3.4). Several similar coils are then piled on top of each other forming the capacitor part of the capacitor unit.

The coils are connected together by wiring which also connects the coils to the lead-in wire. Tin alloys are often used for wiring the capacitor coils. The capacitor units often contain inner fuses. One fuse is connected in series with one coil. The inner fuses disconnect the coils from the grid during faults. Discharge resistors are also connected to the coils. [27]

Aluminum is a commonly used material for conducting plates of capacitors. Aluminum is moulded into thin films, about 4.5 micrometers thick. Aluminum is ideal for high voltage capacitors due to its low resistance, light weight, low cost availability in a large variety of thicknesses and excellent heat transfer [32]. The density, heat transfer and resistivity of aluminum and copper are shown in table 3.1.

Table 3.1: *The density, heat transfer and resistivity of aluminum and copper.*

	aluminum	copper
density (in 25 °C) [33]	2.70 g/cm^3	8.86 kg/cm^3
heat transfer (in 27 °C) [33]	237 W/mK	401 W/mK
resistivity (in 25 °C) [34]	$2.709 \cdot 10^{-8}$ Ωm	$1.712 \cdot 10^{-8}$ Ωm

The difference between the values of heat transfer and resistivity is not tremendous, however aluminum has a smaller density which makes it possible to manufacture items that weight less than the ones manufactured from copper with the same dimensions. Aluminum is cheaper than copper, since the market prize of copper is about four times the prize of aluminum [35].

The insulating material in a power capacitor is usually polypropene. Polypropene is a synthetic thermoplastic polymer [29], that is synthetized by step-growth reaction

from propene [36]. The structural formula of polypropene is seen in Figure 3.6.

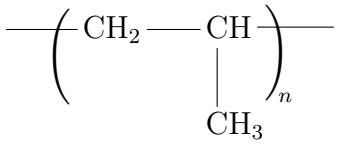

Figure 3.6: *The structural formula of polypropene*

The melting point of polypropene is between 164 to 167 °C, the density is 0.90 g/cm^3 and the resistivity is over $5 \cdot 10^{16}$ Ωm which makes it an ideal insulator for power capacitors [29]. Compared with polyethylene, polypropene has a higher melting point, dielectric constant and breakdown strength.

A polymer is a natural or synthetic long-chain molecule which consists of small simple molecules, called monomers. The monomers are connected to each other by covalent bonds and a polymer is formed from these repeating structural units. Polymers can be homogenous by only one monomer, but polymers with heterogenous monomers are possible. These are called copolymers. Polymers have very high molecular masses ranging from hundreds to a hundred of thousands grams per moles. [37]

Polymers can be classified various ways; based on origin or source, structure, the mode of synthesis or the inter-particle forces. When classified based on origin or source, polymers are divided into natural and synthetic polymers. The structure of the monomer chain varies and there are linear, branched chain and cross-linked polymers.

Polymers are synthetized by addition or condensation reaction, however it is often difficult to find out, if a polymerization happened by either of these reaction types. Polymers can be classified based on the mechanism of combining the monomer units. In that case, polymers are divided into chain growth and step growth polymers. [37]

The final criterion for the classification of polymers is based on the inter-particle forces. The inter-particle forces effect on properties like elasticity, tensile strength and toughness. In this case, polymers are divided into elastomers, thermoplastics and thermosetting polymers. Elastomers are polymers which are highly elastic and can be stretched many times their length, due to very weak attractive forces between monomers. Thermoplastics and thermosetting polymers are polymers, that can be moulded to a shape when heated. The difference between these two is that thermoplastics can be moulded again by heating, when thermosetting polymers can not as they remain in the form they where moulded the first place. [37]

Polypropene is synthetized from propene by a step-growth reaction called Ziegler-Natta reaction [36]. Three types of polypropene are formed in the polymerization reaction: isotactic, atactic and syndiotactic. Most of the commercial polypropene

consists of isotactic form, which is capable of crystallizing, while the rest is atactic form, which is amorphous. The syndiotactic form is also manufactured and it is a form that can crystallize.

Some level of symmetry is found in the isotactic and the syndiotactic polypropene. In the isotactic form, the branches of a polymer chain are located on the same side of the chain. For the syndiotactic polypropene, the branches are located to the alternative sides of the chain. In the atactic polypropene, branches in the polymer chain are placed randomly along the chain. The differences between isotactic, atactic and syndiotactic forms are shown in Figure 3.7. [29]

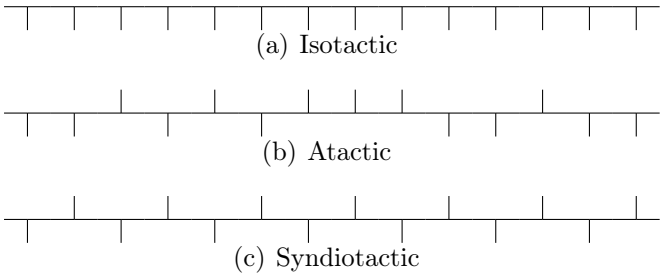

Figure 3.7: *The simplified structure of different types of polypropene. a) The isotactic form, where the methyl groups are located on the same side of the chain. b) The atactic form where the methyl groups are placed randomly along the chain. c) The syndiotactic form where the methyl groups alternate along the chain. [29]*

The mechanical properties of polypropene depend on crystallinity and molecular weight. The molecular weight takes effect on for example viscosity, elasticity and the ability to crystallize, while crystallinity takes effect on for example toughness and rigidity. Polypropene is not easily soluble to any solvent. This is advantageous when manufacturing an impregnated capacitor, where oil is used as an impregnating material. [29]

Polypropene is a good electrical insulator, because it forms a chemically saturated structure. A saturated structure forms when there are no double or triple bonds in the structure. All the electrons are tightly bound to the σ bonds between atoms and as a result, there are no free electrons to work as charge carriers [38]. σ bond is formed, when the atoms strive to attain an octet, 8 electrons, to the valence shell, by forming a covalent bond between atoms. For example, a carbon atom has 4 valence electrons and to attain the octet it has to share an electron pair with another carbon atoms or hydrogen atoms. [31]

A composite is a multi-phase material, where two or more materials are mixed together without dissolving or merging. The materials will not dissolve or merge due to their different physical or chemical properties. The aim of the composite design is to create materials that have better qualities than the original source materials have separately.

The simplest form of composite consists of two materials which form two phases: the matrix and the dispersed phase. The matrix phase is continous and it surrounds the dispersed phase. The concentration of the dispersed phase is usually lower than the concentration of the matrix phase. Usually, composites are mixtures of metals, ceramics or polymers. [39]

A polymer nanocomposite is a material, that consists of a polymer matrix and a small amount of nanoscale additives, called fillers. The matrix phase is a polymer and the dispersed phase consists of silicon oxides, metal oxides or hydroxides, nanoclays or carbon nanotubes. The fillers are usually 1 to 100 nm in size and their concentration in the polymer matrix is around 1 to 10 wt%. The fillers are homogenously dispersed into the polymer matrix. [40]

Nanoparticles can be classified based on the filler aspect ratio or the type of the filler. The aspect ratio of a nanoparticle is the ratio of its longest dimension to its shortest dimension. Fillers are divided into (quasi)-spherical, whiskers and rods or platelet (lamellar) particles based on the aspect ratio. The spherical particles have the smallest aspect ratio and the platelet particles have the largest. When nanoparticles are classified based on the type of filler, they are divided into silicon oxides, metallic oxides, metallic hydroxides, nanoclays and carbon nanotubes [39].

Nanocomposites can be manufactured by the intercalation method, the sol-gel method, the molecular composite method and the direct dispersion method. In the intercalation method, the layered silicate is first swollen in a solvent or within a monomer solution. After that, polymer chains start to form within the interlayer of the silicate.

In the sol-gel method, the nanocomposites are made in the hydrolysis of the constituent molecular precursors and subsequent polycondensation to glass-like form. In the molecular composite method, the polymer matrix is reinforced using molecular rods. In the last method, direct dispersion, nanoparticles are mixed with a polymer without agglomeration. The nanoparticles are modified chemically on their surfaces which increases their compatibility with polymers. [41]

The electrical properties of polymer nanocomposites are not fully known. However, adding a filler to a polymer matrix may improve resistance to electrical erosion. Polymer nanocomposites may be useful as high energy density storage materials since their permittivity can be high (10^{10}). On the other hand, the permittivity can be lower than the permittivity of either of the constituents which is caused by

chain immobilization. Compared with the traditional polymer, nanocomposites can possess improved electrical breakdown strength; it has been observed that the AC (alternating current) and DC breakdown strength increases when a nanocomposite is used with polypropene. This is an interesting result, since safety margins and insulation thicknesses can be reduced in the insulating systems. [42, 43]

So far no capacitors with polymer nanocomposites as the dielectric medium are manufactured commercially. Even though polymer nanocomposites are quite a new technology, they introduce new possibilities for dielectric materials. Compared with the traditional polymers, improvements have been observed in Young's modulus, storage modulus and tensile strength. It has been observed that when the concentration of the clay increases, the tensile strength and Young's modulus increase. These attributes depend on the dispersion of the nanoparticles to the matrix. This may become important, when designing new, thinner insulating systems. [44]

3.2.3 Power Capacitor Bank

A power capacitor bank consists of capacitor units, specific insulators and a metal frame. The capacitor units are connected in series or/and parallel based on the reactive power needed. Usually, the bank stands on a concrete slab. Three types of insulators are used: anti-pollution station post insulators, post insulators and outdoor solid-core post insulators. They are made from porcelain and have cast steel connectors. The frame is usually made from aluminum or steel, depending on the conditions of the place of use or the amount of capacitor units needed. A typical construction of a power capacitor bank is shown in Figure 3.8.

Since the capacitor is a passive component, the power capacitor banks are controlled by switches. Earlier, one of the popular combinations was to use fixed or switched capacitors in parallel or a fixed capacitor and a switched reactor in parallel. Nowadays thyristors are used for controlling capacitors by connecting them anti-parallel. The capacitor bank is controlled with either of these constructions by opening and closing the switches when necessary. [23]

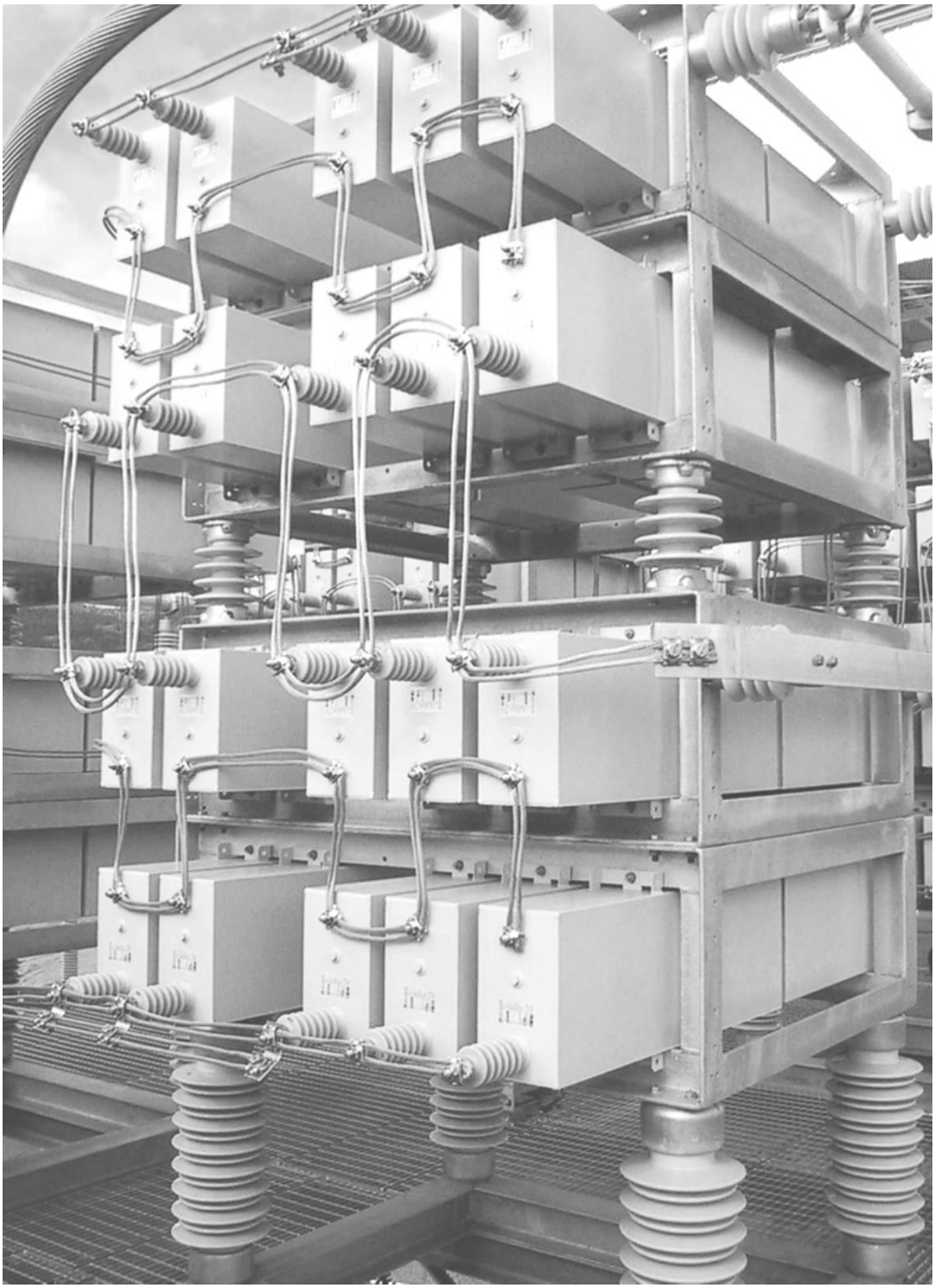

Figure 3.8: *Power Capacitor Bank. The capacitor units are placed on a metal rack and the capacitors are connected through insulators. The larger insulators are anti-pollution station post insulators, post insulators and outdoor solid-core post insulators. Photo provided by Alstom Grid, published with permission.*

4. METHODS AND DATA

First, a literature review about LCA and power capacitors was conducted. The data about the power capacitor bank was acquired from Alstom Grid. A technology matrix and an intervention matrix were constructed from that data. After a few iterative rounds, the LCIA results were calculated and interpreted. Finally, a sensitivity analysis and Monte Carlo simulation was performed to the obtained results.

4.1 Scope and Functional Unit

Two types of product systems were modelled and compared in this study: the traditional capacitor bank and the novel capacitor bank with polymer nanocomposite as the dielectric medium. Based on the discussions with the involved company, the goal of the LCA study was defined to

1. compare the environmental performance of traditional and nanocomposite based capacitor bank and

2. identify possible environmental hotspots, where further eco-design improvements could be directed.

The comparison was made based on the functional unit of "17.25 MVAr of reactive power, over the lifespan of the capacitor bank". The average life span of a capacitor unit is on average around 30 to 40 years. The studied traditional bank was similar to the one presented in Figure 3.8.

For the capacitor bank with polymer nanocomposite insulating medium it was assumed that the efficiency of one capacitor unit improves by 20% when the insulating medium is changed from traditional polypropene to novel polypropene nanocomposite, with silica (silicon dioxide, SiO_2) as the filler material. The ratio of the silica filler in the dielectric medium was assumed to be 4,5 %. It was assumed that when nanocomposite is used, the number of needed capacitor units in the capacitor bank decreases by 20 %.

4.2 LCA Model Details

A full LCA was conducted, which included the supply chain from cradle-to-grave and all relevant environmental impact categories. This is in contrast to carbon footprint studies, which focus on a single impact category and only from cradle-to-factory-gate. A comprehensive analysis allowed a holistic assessment of the product life cycle.

LCI data on materials, assembly, energy use, waste and other manufacturing processes were provided by Alstom Grid. No data referring to the maintenance of the capacitor bank was acquired and hence maintenance was omitted from the model. It was assumed that the finished capacitor banks where transported from Tampere to Hanko by lorry and from Hanko to Rostock by boat.

The used method was process-based LCA. The impact assessment method was ReCiPe Midpoint Hierarchist perspective v 1.08. [16]. The selected LCIA method represents the current state-of-the-art in impact assessment. The impact categories included in the assessment and their units explained are presented in Table 4.1. The abbreviation Eq in the units of various impact categories implies equivalent.

The LCA system was composed to a matrix using process LCA. The primary data for the matrices was acquired from Alstom grid and the secondary data was acquired from ecoinvent database v. 2.2 [17] to model the background processes. The data was analyzed using contribution analysis and normalization using Equations 2.6 and 2.7. The calculations were done with Microsoft Excel utilizing the linear algebra functions.

Table 4.1: *Impact categories and units explained.*

abbreviation	unit	
agricultural land occupation	m^2 a	square meters in one year
climate change	kg CO_2-Eq	kilograms of carbon dioxide equivalent
fossil depletion	kg oil-Eq	kilograms of oil equivalent
freshwater ecotoxicity	kg 1, 4-DCB-Eq	kilograms of 1, 4-dichlorobenzene equivalent
freshwater eutrophication	kg P-Eq	kilograms of phosphorus equivalent
human toxicity	kg 1, 4-DCB-Eq	kilograms of 1, 4-dichlorobenzene equivalent
ionizing radiation	kg U_{235}-Eq	kilograms of uranium isotope 235 equivalent
marine ecotoxicity	kg 1, 4-DCB-Eq	kilograms of 1, 4-dichlorobenzene equivalent
marine eutrophication	kg N-Eq	kilograms of nitrogen equivalent
metal depletion	kg Fe-Eq	kilograms of iron equivalent
natural land transformation	m^2	square meters
ozone depletion	kg CFC-Eq	kilograms of chlorofluorocarbon equivalent
particulate matter formation	kg PM10-Eq	kilograms of particles on the order of micrometers equivalent
photochemical oxidant formation	kg NMVOC	kilograms of non-methane volatile organic compounds equivalent
terrestial acidification	kg SO_2-Eq	kilograms of sulphur dioxide equivalent
terrestial ecotoxicity	kg 1, 4-DCB-Eq	kilograms of 1, 4-dichlorobenzene equivalent
urban land occupation	m^2 a	square meters in one year
water depletion	m^3	cubic meter

4.3 Overview of the Capacitor Bank Production Process

The capacitor units are manufactured and then assembled to capacitor banks at the factory as described in Chapter 3.2. The capacitor banks are then wrapped in plastic film on top of a wooden pallet and transported to the user by lorry and boat. At the site, a concrete slab is moulded as a foundation for the capacitor bank and wiring is installed through the insulators. When the capacitor bank reaches its lifespan, it was assumed that the steel parts are recycled, the polypropene and impregnating oil incinerated and other parts to be transported to landfill.

Besides materials, the capacitor factory needs electricity, cooling and ventilation, district heating, water supply, and waste and waste water treatment to manufacture a capacitor bank. Here it was assumed that the electricity and heat production were combined. Data about waste, electricity and energy was acquired from Alstom Grid along with the data about the materials.

For a capacitor bank, several metals are needed. The case and rack are manufactured from steel and the electrodes in coils are manufactured from aluminum. Tin is used for soldering as well as connection bands and wires. Some small bolts are made from brass. The insulating material is either polypropene (traditional) or polypropene nanocomposite with silica (SiO_2) as the filler material. The data for discharge resistors was acquired from the ecoinvent database [17] since no actual data was found about the materials of resistors. The impregnating oil is a mixture of monobenzyl and dibenzyl toluene, but since no data was available in the database for impregnating oil, the input was assumed to be toluene. The only sources of emissions modelled here were waste incineration and district heating.

It was assumed that after the use phase the steel case is recycled and impregnating oil and polypropene is incinerated. Aluminum and other metals end up in the ash of incineration and are not recycled. The emission factors for the incineration of polypropene and toluene were calculated manually. The incineration reactions of polypropene (4.1) and toluene (4.2) are

$$(C_3H_6)_n + 7.5O_2 \rightarrow 3CO_2 + 3H_2O \tag{4.1}$$

$$C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O. \tag{4.2}$$

When 1 kg of polypropene is incinerated, 3.14 kg of CO_2 is produced. For 1 kg of toluene, the amount is 3.35 kg. The heat of combustion of propene is 48.91 MJ/kg and for toluene 42.44 MJ/kg [45]. The emission factor (4.3) is

$$\text{emissionfactor} = \frac{\text{e}}{\text{E}_{\text{mixture}}}, \tag{4.3}$$

where e is the amount of emissions in kilograms and $E_{mixture}$ the amount of energy in megajoules.

The energy of incineration of a mixture of polypropene and toluene ($E_{mixture}$) can be calculated with Equation 4.4:

$$E_{mixture} = m_{polypropene}E_{polypropene} + m_{toluene}E_{toluene} \tag{4.4}$$

where $m_{polypropene}$ is the mass of polypropene in the capacitor bank and $E_{polypropene}$ the heat of combustion for propene. The second term contains the similar values for toluene.

Emission e is defined with Equation 4.5:

$$e = m_{polypropene}e_{polypropene} + m_{toluene}e_{toluene} \tag{4.5}$$

where $e_{polypropene}$ is the emission factor for polypropene and $e_{toluene}$ the emission factor for toluene.

For the traditional capacitor bank, the amounts of toluene and polypropene are 460 kg and 750 kg. When 4.4 and 4.5 are applied, the energy is now 56200 MJ and the emission is 3890 kg CO_2. The emission factor (4.3) for the incineration of toluene is 0.069 kg CO_2/MJ.

The main direct inputs, outputs and emissions to the product system under study are shown in table 4.2.

The avoided emissions of the district heating in Table 4.2 are the net effect of district heating demand of the factory and the heat produced during waste energy recovery.

Overall, for the traditional capacitor bank the foreground system consisted of 29 processes and the background system 37 processes and for the nanocomposite capacitor bank 30 and 40 processes, respectively.

4.4 Sensitivity and Monte Carlo Simulation

Sensitivity analysis for the technology matrix and intervention matrices was calculated with the formulas presented in Chapter 2.4. The elements with higher than 0.1 value as the sensitivity index where chosen for further study. The uncertainty factors were calculated with the help of the pedigree matrix.

The Monte Carlo simulation was performed with Microsoft Excel using Simulacion 4.0 add-on. Log-normal distribution was selected for randomizing the elements and cumulative distribution was used to represent the results. [19]

Table 4.2: *Main direct inputs, outputs and emissions to the product system under study. The data was acquired from Alstom Grid. The values are rounded to protect the product secret.*

process amount per functional unit	unit	traditional	nanocomposite
Inputs			
steel parts	kg	660	600
disctrict heating	kWh	28	18
electricity	kWh	18	18
porcelain	kg	630	620
transport	tkm	4700	4100
aluminum	kg	280	230
polypropene	kg	750	610
paint	kg	13	10
tin	kg	20	17
impregnating oil	kg	460	380
concrete block	kg	1900	1900
Outputs			
steel to recycling	kg	660	590
district heating	kWh	8500	6900
electricity from energy recovery	kWh	3600	2900
Emissions			
energy recovery	kg CO_2	54000	44000
avoided emissions of district heating	kg CO_2	660	540

5. RESULTS AND DISCUSSION

5.1 Environmental Impacts of Traditional Capacitor Bank and Novel Polymer Nanocomposite Capacitor Bank

The environmental impacts of traditional capacitor bank and novel polymer nanocomposite capacitor bank were studied with the methods presented in Chapter 2. The environmental impacts of the compared capacitor bank alternatives are shown in table 5.1.

Table 5.1: *The environmental impacts of the compared capacitor bank alternatives. The alternative with higher impacts on each category is presented in bold.*

Impact category (unit)	Traditional	Nanocomposite
agricultural land occupation (m^2a)	**933**	800
climate change (kg CO_2-Eq)	**9590**	8010
fossil depletion (kg oil-Eq)	**2950**	2430
freswater ecotoxicity (kg 1, 4-DCB-Eq)	**75**	65
freshwater eutrophication (kg P-Eq)	**2.5**	2.1
human toxicity (kg 1, 4-DCB-Eq)	**3980**	3620
ionizing radiation (kg U_{235}-Eq)	**789**	777
marine ecotoxicity (kg 1, 4-DCB-Eq)	**74**	66
marine eutrophication (kg N-Eq)	**6.3**	5.4
metal depletion (kg Fe-Eq)	**29600**	24700
natural land transformation (m^2)	**2.7**	2.4
ozone depletion (kg CFC-Eq)	0.0003	**0.0004**
particulate matter formation (kg PM10-Eq)	**12.9**	10.6
photochemical oxidant formation (kg NMVOC)	**22.4**	18.9
terrestial acidification (kg SO_2-Eq)	**30.0**	25.5
terrestial ecotoxicity (kg 1, 4-DCB-Eq)	0.51	**0.53**
urban land occupation (m^2a)	**84**	73
water depletion (m^3)	**52**	45

The results show that generally the nanocomposite capacitor bank has smaller impacts than the traditional capacitor bank. On average, the impacts of nanocomposite capacitor are 15% smaller than the traditional capacitors.

However, in a few impact categories the nanocomposite capacitor has lesser impacts: ozone depletion and terrestial ecotoxicity. This is probably due to the as-

sumption that the silica filler in the insulating film was manufactured from silicon tetrachloride ($SiCl_4$) (see equation 5.1).

$$SiCl_4 + 2H_2 + O_2 \rightarrow SiO_2 + 4HCl \tag{5.1}$$

For ozone depletion, the problem appears to be chlorine in the reactant. However, silica (SiO_2) can be manufactured from silane (SiH_4) [46], which may have an effect on the impacts. These impacts are however insignificant based on the normalization results (see table 5.2).

Table 5.2: *The environmental impacts of the two capacitor alternatives, compared with the environmental impacts caused by an average European citizen[16]. The results are normalized using equation 2.7. The alternative with higher impacts on each category is presented in bold.*

impact category	normalization factor impact/PE	traditional PE	nanocomposite PE
agricultural land occupation	4520	**0.21**	0.18
climate change	11200	**0.85**	0.73
fossil depletion	1560	**1.90**	1.56
freswater ecotoxicity	10.9	**6.86**	6.00
freshwater eutrophication	0.41	**6.04**	5.19
human toxicity	590	**6.72**	6.11
ionizing radiation	6260	**0.13**	0.12
marine ecotoxicity	8.5	**8.75**	7.74
marine eutrophication	10.1	**0.62**	0.53
metal depletion	710	**41.54**	34.59
natural land transformation	0.16	**17.15**	14.71
ozone depletion	0.02	0.01	**0.02**
particulate matter formation	14.9	**0.87**	0.71
photochemical oxidant formation	53	**0.42**	0.35
terrestial acidification	34	**0.87**	0.74
terrestial ecotoxicity	8.2	0.06	**0.07**
urban land occupation	410	**0.21**	0.18
water depletion	180	**0.29**	0.25

In order to assist interpretation, the results were normalized by dividing them with the environmental impacts of an average European citizen, also known as person equivalent (PE) (see table 5.2).

For example, the absolute value for climate change for the traditional capacitor bank is 9590 kg CO_2-Eq. When this is compared with the average European value using Equation 2.7, the normalized result is

$$g_{norm_{climatechange}} = \frac{g_{climatechange}}{n_{climatechange}} = \frac{9590 kgCO_2 - Eq}{11200 \frac{kgCO_2 - Eq}{PE}} = 0.85 PE. \quad (5.2)$$

This implies, that the impact of the traditional capacitor bank is 0.85 of the impact of an average European.

For climate change, the normalized impacts are less than for the impact of one European. However, the impact is still significant since the value was close to the average impact. For metal depletion and natural land transformation, the normalized results were multiple times greater than the average impacts. All of these three impact categories (climate change, metal depletion, natural land transformation) presented either high values or otherwise significant impacts, and thus these three were chosen for the contribution analysis. In the contribution analysis, the main culprits that contribute the most for each impact category were defined.

The normalization can often be biased. This effects especially on the normalized results of toxicity [47, 48]. For this reason, the toxicity of metals is often overestimated in LCIA and hence impact categories with toxicity were not analyzed further even though they represented relatively high impacts after normalization.

5.2 Identifying the Environmental Hotspots

The results of the contribution analysis of climate change are shown in Figure 5.1. The top six processes that contribute the greatest impacts are shown separately, the rest of the processes are added together and the negative impacts are also added together. The greatest impacts arise from the energy recovery of the capacitor parts. This process involves the incineration of the materials inside the capacitor steel case, mainly from the incineration of toluene and polypropene. However, the actual impregnating oil is not toluene, but a mixture of monobenzyltoluene and dibenzyltoluene. When toluene (C_7H_8) is compared with monobenzyltoluene ($C_{14}H_{14}$) and dibenzyltoluene ($C_{21}H_{20}$), it is seen that the amount of carbon compared with hydrogen is greater. This may cause more CO_2 emissions compared with the results that were obtained in this study.

It was assumed that during recycling the capacitor insides are incinerated and the energy is used to avoid additional heat and electricity production. This avoided burden was credited to the product, as were the benefits of recycling metals.

Other than that, manufacturing of toluene for the impregnating oil and the manufacturing of polypropene increase the impact on climate change. Furthermore, three processes that handle metals contribute to climate change, including aluminum production and steel and steel product manufacturing. The results for the nanocomposite capacitor bank are similar in comparison with the traditional capacitor bank. Overall, the impacts of the nanocomposite capacitor bank are lesser than the im-

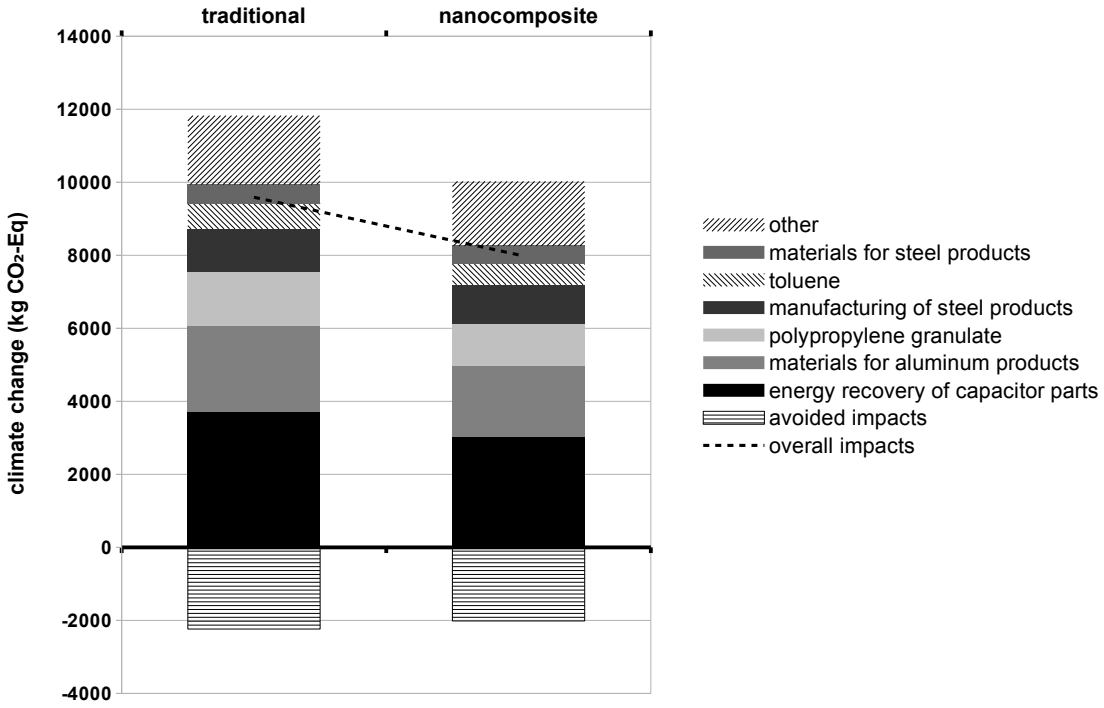

Figure 5.1: *Main processes contributing to climate change. The values in the figure are absolute. The avoided impacts are negative contributions also known as impacts that decrease the overall impact.*

pacts of the traditional capacitor bank: it was assumed that smaller number of nanocomposite capacitor units were needed to produce the same amount of reactive power.

The nanocomposite film contributes about 2 % of the overall impact of climate change. This is relatively small impact when compared with energy recovery (38 % of the overall impact) and aluminum production (24 % of the overall impact). However, the overall impact of the nanocomposite capacitor bank is about 20 % smaller. This implies that even though nanocomposites have an impact on the climate change, the overall impact is fairly small in comparison with the traditional capacitor bank due to decrease in the amount of materials used.

The top five processes that contribute the greatest impacts to metal depletion (see Figure 5.2) are shown separately, the rest of the processes presented as they were in the case of climate change. When looking at the results of contribution analysis of metal depletion (Figure 5.2), the major impact is caused by tin. Tin is used for welding in the capacitor units. Even though the amount of tin needed is small, it contributes significantly to metal depletion. The abundance of tin in Earth's crust is relatively small, around 2 ppm when the abundance of iron is 56

000 ppm and aluminum 82 000 ppm [49]. This may be one of the reasons, why tin contributes greatly to the metal depletion.

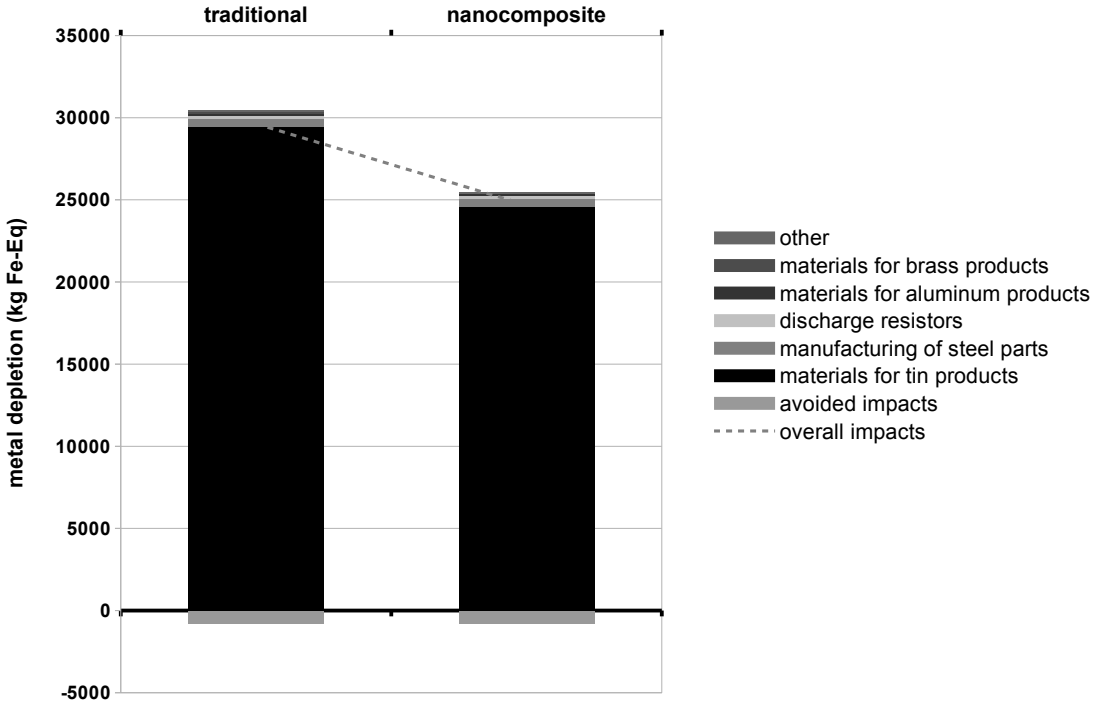

Figure 5.2: *Main processes contributing to metal depletion. The values in the figure are absolute. The avoided impacts are negative contributions also known as impacts that decrease the overall impact.*

It was assumed that the nanocomposite capacitor bank has similar steel rack as the traditional one, but it was assumed that the number of capacitor units used is smaller when nanocomposite is used as the dielectric medium. This implies, that a smaller rack could be used for the nanocomposite capacitor bank and hence the impacts might be even smaller. This could decrease impacts from the steel processes which can have an effect on the other impact categories too. Overall, the impact of steel is very small in comparison with tin in the metal depletion impact category.

When the impact of tin and nanocomposite in metal depletion is compared, it is seen that the impact of nanocomposites is 0.04 % of the overall impact when the tin process contributes 99.7 % of the overall impact. From this point of view, even though the use of nanocomposites contributes a little on the metal depletion impact category when nanocomposite is used the overall impact of tin decreases. In conclusion, the use of nanocomposites decreases the amount of metals needed in the manufacturing process.

When compared with the average impacts, the impacts of metal depletion clearly

show that the capacitor units use a lot of metals. The average European value is small, since most of the mining is done outside Europe and is not therefore included in the normalization figures which were used. However, it is noteworthy that the steel parts are not significant in the total metal depletion. Only the manufacturing losses are considered since it was assumed that the steel parts were fully recycled in the life cycle.

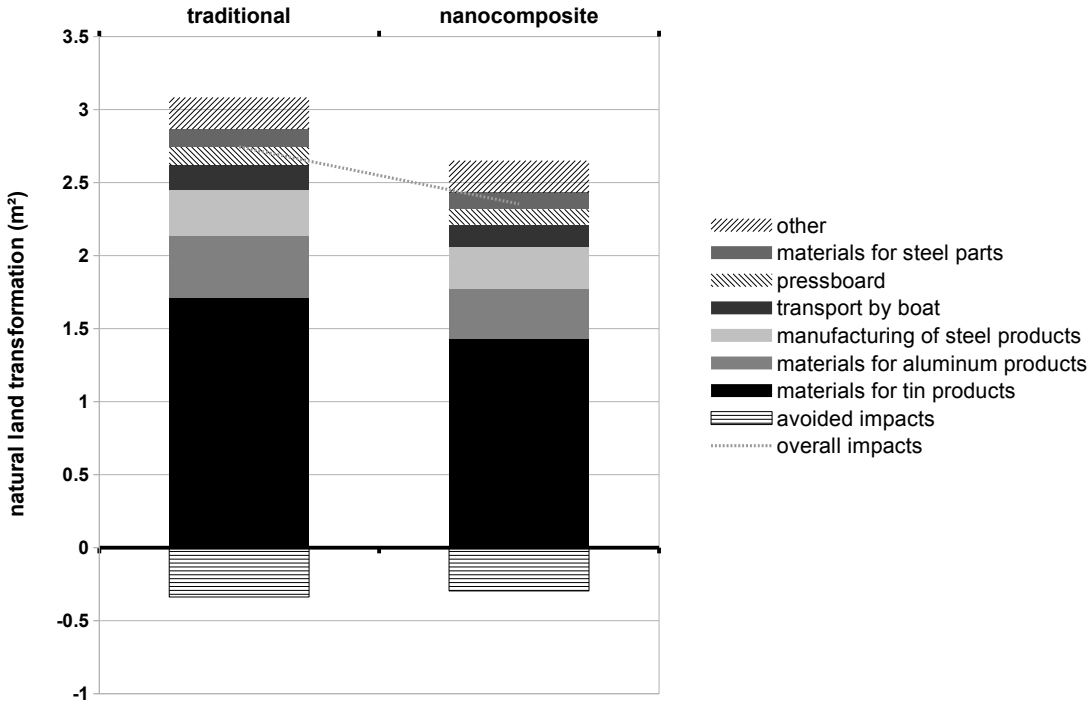

Figure 5.3: *Main processes contributing to natural land transformation. The values in the figure are absolute. The avoided impacts are negative contributions also known as impacts that decrease the overall impact.*

The top six processes that contribute the greatest impacts to natural land transformation (see Figure 5.3) are shown separately, the rest of the processes are presented as in the case of climate change and metal depletion. For natural land transformation, the top three contributors appear to be processes that handle metals (Figure 5.3). In addition, boat transport, which was assumed to be a barge from Hanko to Rostock, contributes to the natural land transformation. This is caused probably by the requirement for harbours and by the fuel supply chain of transportation. The use of nanocomposites increases natural land transformation impact by 1.3 %, but like mentioned earlier, the use of nanocomposite to limit the amount of capacitor units needed, decreases the natural land transformation overall impact by 15 %.

The large impact of metal processes can be explained by the small amount of mines in Europe; most of the metals are imported to Europe. Therefore, Europe has little land transformation on average. Overall, substituting tin and using fully recycled aluminium would reduce the land use impacts considerably.

5.3 Uncertainty Analysis

Uncertainty analysis was performed to three impact categories: climate change, metal depletion and natural land transformation since these three were the impact categories studied further in the LCIA. Based on the formulas presented in Chapter 2.4, inputs and outputs were chosen for Monte Carlo simulation; with the traditional capacitor bank seven inputs/outputs were selected for the technology matrix as well as for the intervention matrix. With nanocomposite capacitor bank, eight inputs/outputs were selected for the technology matrix as well as for the intervention matrix.

The inputs and outputs that were chosen for the Monte Carlo simulation are presented in table 5.3 and 5.4. The criteria for candidates for the Monte Carlo simulation was, that the index should be greater than 0.1 or smaller than -0.1 and in the $\mathbf{A}$ and $\mathbf{B}$ matrices the value should be other than 1. Components that had value 1 in the matrices were considered connection variables and hence omitted from Monte Carlo simulation.

Table 5.3: *The selected inputs/outputs of the technology matrix for the Monte Carlo simulation.*

Input/output (unit)	Sensitivity index	Uncertainty factor	Median
Traditional capacitor			
energy recovery of capacitor parts (MJ)	0.2555	1.573	53724
polypropene film, coiling (kg)	0.1948	1.431	34
aluminum foil, coiling (kg)	0.2626	1.431	12.5
wiring for capacitor, welding (kg)	0.1451	1.431	0.137
wiring for capacitor, coiling (kg)	0.3684	1.431	0.348
tin at regional storage, wiring (kg)	0.6098	1.431	0.960
tin at regional storage, fuse manufacture (kg)	0.3837	1.431	0.348
Nanocomposite capacitor			
energy recovery of capacitor parts (MJ)	0.2502	1.573	43956
nano-polypropene film, coiling (kg)	0.2015	1.431	34
aluminum foil, coiling (kg)	0.2571	1.431	12.5
polypropene granulate, at plant (kg)	0.1439	1.147	0.955
wiring for capacitor, welding (kg)	0.1426	1.431	0.13698
wiring for capacitor, coiling (kg)	0.3619	1.431	0.348
tin at regional storage, wiring (kg)	0.6202	1.431	0.960
tin at regional storage, fuse manufacture (kg)	0.377	1.431	0.348

Table 5.4: *The selected inputs/outputs of the intervention matrix for the Monte Carlo simulation.*

Input/output (unit)	Sensitivity index	Uncertainty factor	Median	Impact category
Traditional capacitor				
energy recovery of capacitor parts (kg)	0.3882	1.663	0.0693	climate change
steel product manufacturing (kg)	0.1223	1.05	1.795	climate change
polypropene granulate, at plant (kg)	0.1539	1.05	1.973	climate change
tin, at regional storage (kg)	0.9936	1.05	1486.2	metal depletion
steel product manufacturing (kg)	0.1154	1.05	0.000481	natural land transformation
tin, at regional storage (kg)	0.6233	1.05	0.0864	natural land transformation
aluminum, production mix (kg)	0.1536	1.05	0.00153	natural land transformation
Nanocomposite capacitor				
energy recovery of capacitor parts (MJ)	0.3801	1.6632	0.0693	climate change
steel product manufacturing(kg)	0.1335	1.05	1.795	climate change
polypropene granulate, at plant(kg)	0.1439	1.05	1.973	climate change
steel converter, unalloyed, at plant(kg)	0.1197	1.05	1.609	climate change
tin, at regional storage (kg)	0.9972	1.05	1486.2	metal depletion
steel product manufacturing (kg)	0.1218	1.05	0.000481	natural land transformation
tin, at regional storage (kg)	0.6075	1.05	0.0864	natural land transformation
aluminum, production mix at plant (kg)	0.1466	1.05	0.00153	natural land transformation

The results of Monte Carlo simulation are presented in figures (5.4),(5.5) and (5.6). They are shown as cumulative distribution graphs. Monte Carlo simulation results for the nanocomposite capacitor bank are shown in grey and the results for the traditional capacitor bank are shown in black.

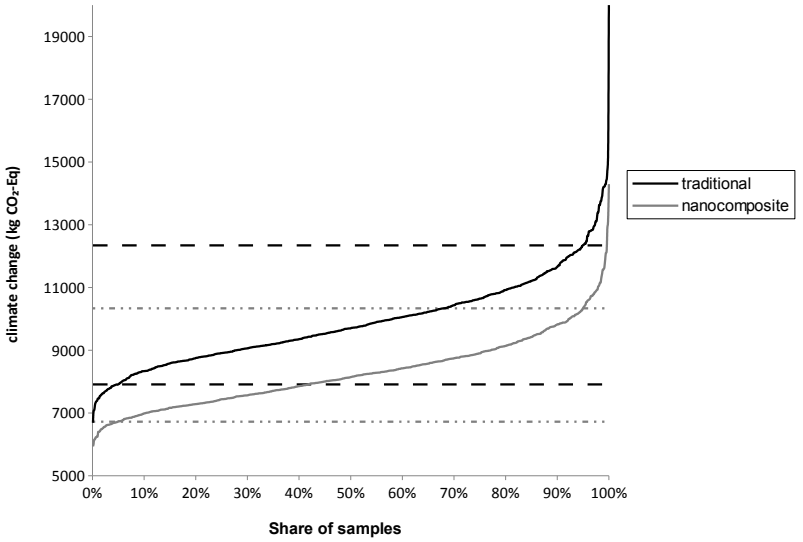

Figure 5.4: *The Monte Carlo simulation results of climate change. The cumulative distribution function of traditional (black) and nanocomposite capacitor bank (grey). 90% confidence intervals are shown with dashed line for traditional capacitor bank (black) and nanocomposite capacitor bank (grey).*

It is seen that the graphs do not cross in either of them: climate change, metal depletion and natural land transformation. Hence, it can be assumed, that nanocomposite capacitor bank has smaller environmental impacts on at least these three impact categories. However, 95% cover is overlapping which indicates that the superiority of the nanocomposite capacitor bank is not 100% certain. 95 % cover is defined by dividing and multiplying the median with the uncertainty factor [19, 50]. This implies, that there are some situations, where the traditional capacitor bank may have lesser impacts than the nanocomposite capacitor bank. This results in large parameter space which further analysis is out of the scope of this thesis, but an interesting option for future research.

In the results of nanocomposite capacitor bank, the median is also generally smaller in the nanocomposite capacitor bank results.

In conclusion, based on the uncertainty analysis, the nanocomposite capacitor bank seems to have smaller environmental impacts than the traditional capacitor bank. Nanocomposite capacitor bank dominates the traditional one stochastically which implies that the nanocomposite bank is better for the environment than the

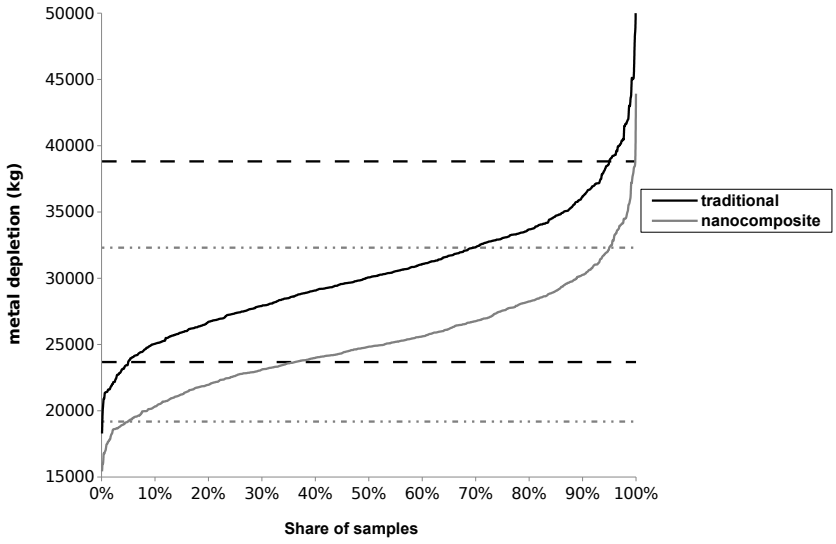

Figure 5.5: *The Monte Carlo simulation results of metal depletion. The cumulative distribution function of traditional (black) and nanocomposite capacitor bank (grey). 90% confidence intervals are shown with dashed line for traditional capacitor bank (black) and nanocomposite capacitor bank (grey).*

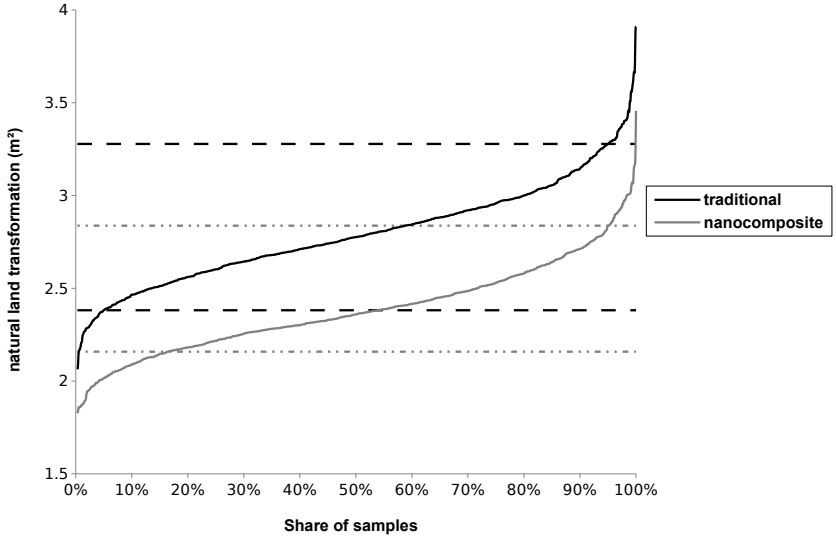

Figure 5.6: *The Monte Carlo simulation results of natural land transformation. The cumulative distribution function of traditional (black) and nanocomposite capacitor bank (grey). 90% confidence intervals are shown with dashed line for traditional capacitor bank (black) and nanocomposite capacitor bank (grey).*

traditional one. Although, there is some overlapping in the graphs and hence it is impossible to say if the nanocomposite capacitor bank always has smaller impacts,

than the traditional one. The superiority of nanocomposite capacitor bank can be ensured by minimizing the variables that were chosen for Monte Carlo simulation. This means that the variables should be taken into account as central variables for the eco-design.

5.4 Discussion

The objectives of this study were:

1. to investigate, what kind of results can be attained with LCA methodology and if they can assist in the design and the manufacturing of power capacitors
2. to perform a LCA for a capacitor bank that is manufactured and used at the moment
3. to perform a LCA for a novel capacitor bank that has polymer nanocomposite as a dielectric medium and
4. to find possible hot spots in the manufacturing process of both of these constructions.

As a whole, the nanocomposite capacitor bank has lesser environmental impacts than the traditional capacitor bank. The major decrease in impacts was found in the need of metal materials and lesser amount of polypropene and impregnating oil to be incinerated during recycling.

The major problems seem to arise from the use of tin and incineration of impregnating oil and polypropene. If CO_2 recovery was possible, the emissions of CO_2 would decrease significantly. Less land would be necessary for the mines, if tin recycling was improved or tin could be replaced and hence decreasing the amount of raw tin used. Additionally, the steel rack for the nanocomposite capacitor bank was assumed to be the same as for the traditional capacitor bank. However, the number of capacitor units is smaller when nanocomposite is used, which implies that the reduction of capacitor units may decrese the amount of steel needed for the rack.

Overall, tin is one of the major contributors for the impacts. The abundance of tin in Earth's crust is relatively small in comparison with other metals [49] meanwhile the demand for tin has increased substantially in the recent years, when the production has decreased. The metal content of the ore is declining due to richer deposits being exhausted. Eventhough this may increase the market prize of tin, the metal is necessary in the electronic industry for welding and the circuits [51]. Currently, there are no alternatives for tin, and hence the recycling of tin should be considered as well as the overall tin usage should be reduced.

The amount of tin in the models deserves some critical consideration. The connection bands and wires are manufactured from a copper/tin mixture. Since the

information about the mixture ratio was not available, the connection bands and wires have been modelled as pure tin. If the real mixture ratio was known, the model would be more accurate and the effect of tin in metal depletion and natural land transformation might decrease. However, the copper processes could still increase some other impacts.

The impregnating oil in the capacitor units was assumed to be toluene even though the actual impregnating oil is a mixture of dibenzyltoluene and monobenzyltoluene. Data was not available for these two in the used databases. The impregnating oil impacts heavily on climate change and if data about dibenzyltoluene and monobenzyltoluene were available in the ecoinvent database [17] or from a manufacturer for example, the model would be more accurate. According to the incineration reaction of polypropene (4.2) 1/7 moles of CO_2 is produced during the incineration. When the incineration reactions of monobenzyltoluene (5.3) and dibenzyltoluene (5.4) are observed,

$$C_{14}H_{14} + 17.5O_2 \rightarrow 14CO_2 + 7H_2O \tag{5.3}$$

$$C_{21}H_{20} + 26O_2 \rightarrow 21CO_2 + 10H_2O \tag{5.4}$$

it is seen that the incineration of 1 mole of monobenzyltoluene produces 1/14 moles of CO_2 and 1 mole of dibenzyltoluene 1/21 moles of CO_2. The amount of CO_2 produced is different than in the incineration of toluene and thus the impact result for climate change may be incorrect on the energy recovery part.

Even though massive amount of porcelain (about 600 kg) is used for insulating purposes in the capacitor bank, they have a small environmental impact. It is suggested that the metal bushings of insulators contribute more than the actual porcelain part [11].

Uncertainty analysis was also performed with sensitivity analysis and Monte Carlo simulation. These results also suggest that nanocomposite capacitor bank has smaller impacts than the traditional capacitor bank. However, the conclusions are rather rough in comparison with the main input parameters.

When considering the use of LCA, it should be noted that LCA is laborious and time-consuming assessment method. The construction of the LCA model and the availability of data are the major challenges. The results are not absolute, they are suggestive and only estimates for the actual impacts. The results could be defective, due to issues with the data, the poor availability of data or poor constructional choices within the setup of the model.

When the availability of data is poor or the data quality is somewhat false, several assumptions and decisions must be made in order to conduct the assessment.

If the data quality is poor or false, it may affect the results dramatically. For example, in this study, the connection bands and wires were assumed to be pure tin, which was the main culprit contributing especially metal depletion and natural land transformation. However, the connection bands and wires were manufactured from a mixture of copper and tin. Therefore, the actual amount of tin in one capacitor battery is smaller and hence the true impact of tin may be lesser than the results suggest.

As was mentioned in the Introduction, several LCA studies have been performed to analyze energy production. However, the interest towards the environmental impacts of T&D systems is starting to grow and only a few studies about the components of T&D have been performed. According to other LCA studies [5, 10], most of the impacts in power T&D systems arise from power losses. Due to this, improving the efficiency of grid components might contribute lesser impacts. Furthermore, when the efficiency of the components increases, the needed amount of materials may decrease. This may have an effect on the environmental impacts of the grid.

There is a growing interest towards more environmentally friendly products and production processes. The European Union has declared some specific directives such as 2010/75/EU about industrial emissions. The directive defines guidelines for industrial production for example for limiting, recycling and decreasing waste and improving energy efficiency. This raises the question whether it would be less expensive for industry to consider and model the environmental impacts of their products prior to starting the full-scale production. In this case, LCA is one of the most valuable tools available. Furthermore, LCA is a powerful tool when assigning eco-labels to various products or when comparing two similar products and their environmental performance.

When successful, LCA can show the possible hotspots in the manufacturing process. In this study, for example, it was shown that chlorine in the reactant $SiCl_4$ may increase the impacts of ozone depletion and terrestial ecotoxicity. Also, it was seen that the greatest impacts were caused in most of the impact categories by metal processes. Even though LCA does not address financial and economical aspects, using less metals may also affect by lowering the costs of one capacitor bank. This result would have been difficult to attain without the use of LCA.

In this study, the assumed number of needed capacitor units was an educated guess. In the future, a new LCA should be considered if and when the actual improvement in the voltage gradient and in other features of the nanocomposite capacitor are known. For now, it is not known how many capacitor units can be left out if the polypropene film is replaced with the nanocomposite and if the use of the nanocomposite will effect in the other aspects of the capacitor unit such as the used materials. Furthermore, the LCA model itself should be further developed

and defined to attain more accurate results.

6. CONCLUSIONS

The environmental impacts of traditional capacitor bank and nanocomposite capacitor bank were assessed in this study. The impact assessment was conducted using Life Cycle Assessment methodology using the equations described in Chapter 2.3.

As an overall result, the nanocomposite capacitor bank has lesser impacts on most of the impact categories. This is mostly due to lesser amount of materials used. However, few hotspots can be discovered in both:

- tin production
- production of impregnating oil and polypropene
- various other metal processes and
- the energy recovery of capacitor parts, including the incineration of polypropene and impregnating oil.

These contribute significant impacts, especially in the impact categories such as climate change, metal depletion and natural land transformation.

These results can be useful in capacitor design. For example, the results of LCIA clearly show, that a decrease in material amounts decreases the environmental impacts. The environmental impacts of a capacitor bank could be decreased by for example

- decreasing the amount of tin used
- recovering carbon dioxide during disposal and incineration
- recycling metals.

The demand for more environmentally friendly products and processes has increased in recent years. The global warming, greenhouse gases, land use and depletion of rare metals cost more besides being unfriendly to the environment. It may be possible to save money by producing more environmentally friendly products and using less materials besides saving the planet.

For future work, the data and the LCA model for the capacitor bank has to be further developed. Also more accurate data is necessary and for example data about the nanocomposite capacitor bank are mostly educated guesses since the

nanocomposite capacitor bank is still hypothetical and in the design phase. Based on the data available from the experimental nanocomposite capacitor design, very little can be said about the actual amount of material and production efforts needed. At this moment, it is also difficult to assess, if the improvement in the efficiency of the nanocomposice capacitor bank will be 20 % (which was assumed here) or something else.

The LCA results indicate clearly that especially for tin an alternative material in electronics should be searched. Even though nanotecnology could decrease the environmental impacts, it will not solve completely the major issues pointed out in this thesis work.

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